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Natural and Artificial Weathering of Bedrock Overburden Associated with Open-Pit Coal Mines--S.W. Alberta

by

Ⓒ Louis Anthony D. Kamenka

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
MASTER OF SCIENCE

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Frank W. Schwartz

Lionel E. Jackson

Date Oct 14, 1983

DEDICATION

I wish to dedicate this thesis to those involved with reclamation of open pit coal mines. To my family and friends for believing in my pursuit of this research and to my parents who I extend my deepest gratitude for showing myself an open-minded approach to life and providing me with the opportunity, through their sacrifices, to explore and experience this unique path.

ABSTRACT

Bedrock lithologies disposed of during open-pit coal mining at Grassy Mountain have experienced 29 years of natural chemical and physical weathering. Rates of physical deterioration varies for each lithology with fine grained rocks ie. shale-silty shale experiencing the most rapid physical breakdown. Physical degradation of rock in overburden piles is initially induced by man but later controlled by wetting-drying and frost-freeze cycles. Physical breakdown of rock exposes broken mineral bonds a[illegible]esh mineral overfaces to the chemical weathering environment. An artificial weathering environment which closely resembled but accelerated rates of weathering occurring at Grassy Mountain was achieved using soxhlet extraction apparatus. Crushed fresh rock samples representing (1) different lithologies within Grassy Mountain overburden and (2) three different particle sizes were artificially weathered for 3 to 4 weeks.

Artificially produced leachates were analysed at one week intervals and their chemistry determined. Variations in particle sizes had no effect on leachate pH but did alter the concentration of ions. Fine particles yield leachates with higher initial cation concentrations than coarser particles but their leachate concentrations dropped more rapidly with time and to lower coarser particles leachates. Sandstone siltstone produced similar leachate chemistries and concentrations upon artificial weathering. Shale consisting of more clay minerals produced leachates with higher sodium and potassium concentrations than sandstone-siltstone leachates. All

lastic lithology leachates were alkaline, similar to local pristine waters. Coal leachates were acidic, pH 5.0-5.4 and contained a greater variety of metallic ions at higher concentrations than clastic lithology leachates.

Leachates produced during artificial rock weathering yeild similar chemistries and similar trends to naturally derived leachates.

Sulphate concentrations and total alkalinity of leachates produced during artificial weathering reached values observed in local pristine waters in 3 to 4 weeks. Potassium and sodium concentrations in artificially produced leachates acquired pristine concentrations in 8 to 16 weeks respectively. Leachate pH from natural and artificial overburden weathering will remain alkaline unless large volumes of coal are permitted to weather on their own. Water chemistry affected by overburden weathering should remain within limits described as permissible by Environment Canada. Only iron and manganese concentration exceeded these limits in a few sporadic underground mine effluents. Soil development on bedrock overburden will be slow, possibly hundreds of years as weathering processes are slow and the environment harsh to plant growth.

ACKNOWLEDGEMENTS

I wish to acknowledge the following individuals and firms for their support to this research. Dr. Nathan Rutter, University of Alberta, Edmonton, who supervised this project, Dr. Lionel Jackson, Geological Survey of Canada, Calgary, who provided data, advise and reviewed many aspects of this thesis. Esso Resources Canada Ltd. for financial support as grants, the Geological Survey of Canada who allowed use of their laboratory facilities, lab technicians at the University of Alberta for their section preparation and assistance in operating the Atomic Absorption Unit. A special thanks to Louise Burke who endured the frustrating task of proof reading.

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CHAPTER 1

THE PROBLEM

Introduction

An increased demand for metallurgical coal found within the Rocky Mountains of Alberta and British Columbia has resulted in large-scale open pit mining operations, generating tremendous volumes of discarded overburden. Each year the volume of rejected material from these mines surpasses that of the Frank Slide, 71,000,000 cubic metres. Reclamation has now become an essential element of the mining operation. A well conceived reclamation program integrated into each stage of mining activity is now required by law before the commencement of mining (Land Surface Conservation and Reclamation Act, 1973, Alberta). Knowledge of the rates, and processes by which these overburden materials weather and the by-products is insufficient and cannot be readily compared from one region to another.

The objections of this thesis are to determine the processes and products of coal overburden weathering in the Crowsnest Pass area of the Rocky Mountains. This was accomplished by literature research, field studies and artificial weathering of rock wastes from a specific control site--Grassy Mountain.

Investigations were carried out on the following:

(1) Weathering by-products from specific lithologies; shale, sandstone, siltstone, coal.

(2) Weathering by-products from mixtures of lithologies equivalent to overburden spoil piles at Grassy Mountain.

(3) The significance of particle size with respect

to the rate and process of weathering.

(4) The relative susceptibility of various lithologies to either physical or chemical weathering.

(5) The application of results to the prediction of future changes in water chemistry of streams draining from or in contact with weathering overburden.

(6) Duration of weathering required for overburden materials to break down into specific grain sizes resulting in the formation of soils.

(7) Identify overburden lithologies and grain sizes which contribute the highest proportion of elements, cations and anions to the weathering system.

The results from this investigation could provide information enabling better methods of reclamation to be implemented during each phase of overburden disposal at the mine site.

CHAPTER 2

THE STUDY AREA

2.1 General Setting of the Study Area

2.1.A Location

The area is located within the Front Ranges of the Rocky Mountains, 7 kilometers north of Blairmore in the Crowsnest Pass region of Southwestern Alberta, approximately 120 kilometers west of the city of Lethbridge. Present access to Grassy Mountain is by gravel road constructed from Blairmore by mining companies. (Western Canadian Collieries, 1940's) Blairmore lies off highway #3, a major east-west artery passing through the Crowsnest Pass. (Maps 1 and 2)

Grassy Mountain, the site of an abandoned open pit coal mine was chosen as the most suitable site for the purpose of this study. The factors which contributed to the selection of this area are listed below:

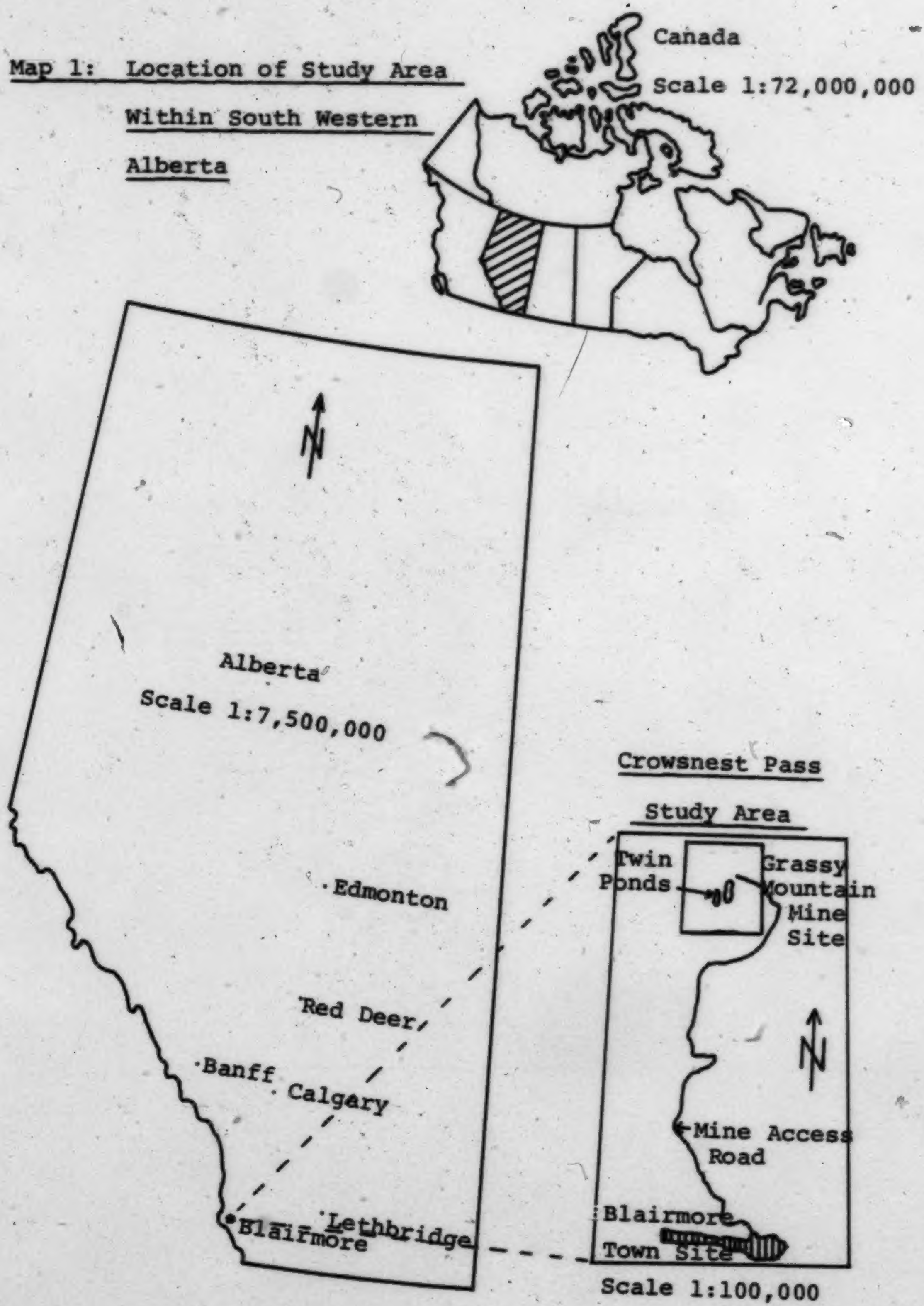
(1) The study area described is the type section for the Kootenay Formation. (Norris, 1959)[49]

(2) Petrological, lithological and history of deposition for rock material extracted during previous mining is well documented. (J. Rapson, MSc Thesis, 1963)[58]

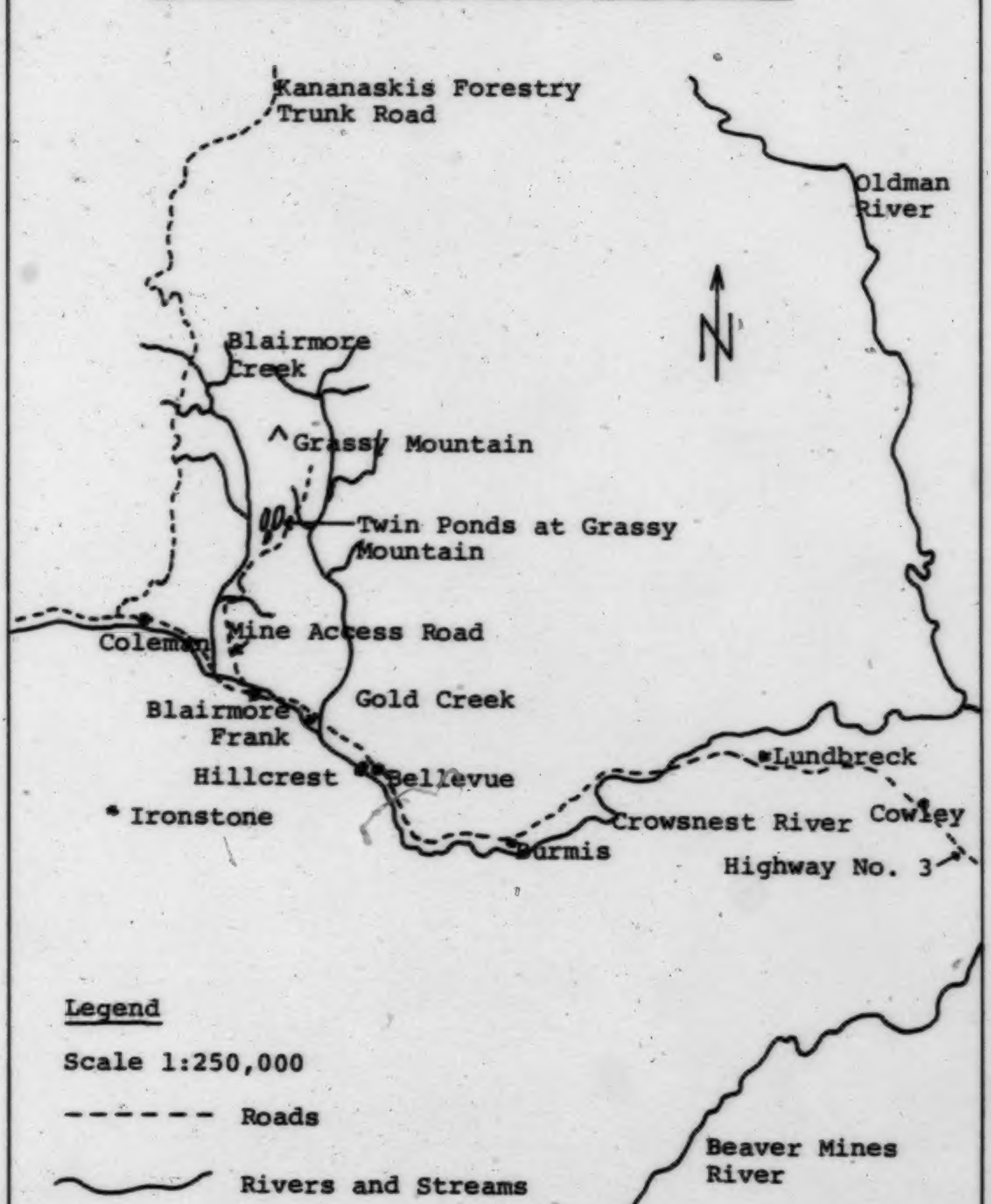
(3) Climatic records are complete from the mid 1940's (Environment Canada)[18] for the Crowsnest Pass area and specific observations have been made at the mine site (Consol, 1975)[11]

(4) Previous open pit mining activity has created overburden piles which remain unreclaimed. It is therefore possible to observe the results of natural overburden weath-

Map 1: Location of Study Area Within South Western Alberta


Canada
Scale 1:72,000,000
N
Alberta
Scale 1:7,500,000
Edmonton
Red Deer
Banff
Calgary
Blairmore
Lethbridge
Crowsnest Pass Study Area
Twin Ponds
Grassy Mountain Mine Site
N
Mine Access Road
Blairmore Town Site
Scale 1:100,000

Map 2: Location Map Crowsnest Pass Area


Kananaskis Forestry Trunk Road
Oldman River
Blairmore Creek
Grassy Mountain
Twin Ponds at Grassy Mountain
Mine Access Road
Coleman
Gold Creek
Blairmore
Frank
Hillcrest
Bellevue
Ironstone
Lundbreck
Crowsnest River
Cowley
Burmis
Highway No. 3
Legend
Scale 1:250,000
Roads
Rivers and Streams
Beaver Mines River

ering over a known period of time.

(5) The area is easily accessible by a mine road.

(6) Water chemistry of springs, streams and lakes within disturbed and natural sites have been closely monitored. (Jackson, 1978[28]; Consol, 1975[11])

(7) Groundwater systems which emerge as springs at the base of spoil piles are analogous to the experimental method of artificial weathering employed during this research.

2.1.B Topography

The area is characterized by rolling to mountainous terrain with local elevations ranging from 1280 to 2070 metres above sea level. Grassy Mountain is a north-south orientated ridge approximately 5 kilometers long and with natural slopes averaging 30 percent. Maximum inclines up to 60 percent are present on the mountain. The southern portion of Grassy Mountain, immediately north of the twin ponds (Map 1), was selected for study. Much of the natural topography has been altered by open pit activity resulting in decreased slopes due to disposal of overburden filling valleys or increased slopes, ie. highwalls in excess of 60 metres and 70°, created by V-cut trenches. Approximately 200 hectares of Grassy Mountain have been altered due to previous mining activity. (Consol, using areal photo-mosaics).

2.1.C Surface Water and Drainage

Flooding of unreclaimed open pits in the southern flanks of Grassy Mountain has resulted in the formation of three ponds. One small bog located 1 kilometer east of the artificial ponds (Map 2) comprises the only natural body of water within the study area. The east side of Grassy Mountain is drained by Gold Creek and its tributaries while the western and southern slopes drain into Blairmore Creek. Both streams flow southward joining the Crowsnest River at Frank and Blairmore respectively. Minor drainage from springs located at the base of spoil piles and open pit trenches flow into both creeks and the artificially formed lakes. These springs carry evidence of chemical alterations occurring within the overburden piles.

2.2 Previous Research and Mining History of the Grassy Mountain Area

2.2.A Previous Research

The economic importance of the clastic sediments in southwestern Alberta have long been known. Dawson, G.M., (1886)[13] proposed to call the lower part of the Mesozoic section, between the United States border and Bow River, the Kootenie Series. This name was derived from a tribe of Indians which hunted in this area. Later that year Dawson gave a detailed description of the Kootenie Series, taking into account its floral content and stratigraphic relation to beds existing above and below the Series. The Dawson proposal and description became the first definition of the Kootenie Series. The definition of the Kootenie Series included the present day Fernie Group, the presently known and accepted Kootenay Formation and part of the overlying Blairmore Group.

The Kootenie Series was subjected to two major reclassifications. Leach (1912) called the lower part of the Series which consisted of dark marine shales the Fernie Group, the remainder of the Series he renamed the Kootenay Formation. Rose (1917) further restricted the Kootenay Formation by recognizing an unconformity at the base of a conglomerate located in Leach's upper portion of the Kootenay. Rose then defined the top of the Kootenay at this unconformity and included the conglomerate into the present Blairmore Group.

Norris (1959)[49] proposed the type section for the Kootenay Formation be considered as the south face of Grassy Mountain, 8 kilometers north of Blairmore, the study area of this thesis. Norris divided the Kootenay Formation into four units, termed respectively from the lowest, the Moose Mountain, Adanac, Hillcrest and Mutz Member. The section here is completely exposed along mine roads and although faulted and folded, a restored section was easily obtained. The year 1975 marked a new era in Grassy Mountains's research history. Consolidated Coal Company of Canada (Consol)[11] began to research the environmental impact of previous mining disturbances and the geology of the area as part of a proposal for possible future mining of coal. R. M. Hardy and Associates were employed by Consol to investigate climatic conditions, water chemistry, overburden types and properties of the area, research which continued extensively over a two-year period.

Dr. Lionel Jackson of the G.S.C. (1977)[28] began to monitor water chemistry from springs draining coal overburden piles and lakes occupying pits caused by previous open pit mining.

Samples were collected and analyzed at 1 month intervals between May and October in both 1977 and 1978. Data obtained from these studies were used in conjunction with water chemistry results obtained during the present research.

2.2.B Previous Mining History

Coal mining in the Grassy Mountain region began around the turn of the century. Western Canadian Collieries Ltd. acquired mineral rights for most of the Crowsnest area in 1902 and began extracting coal from underground mines at Lille, presently a ghost town, located 5 kilometers east of Grassy Mountain. The mine at Lille closed in 1912 at which time 3 new underground mines were opened on Grassy Mountain. These mines operated until 1947 when Western Canadian Collieries Ltd. began open pit mining on the southern portion of Grassy Mountain. Open pit mining continued until 1960. During this time 3.5 million tons of coal were extracted at a maximum stripping ratio of 2:1. 1960 marked the termination of all mining leaving more than 200 hectares of unreclaimed overburden and land, a scar which Grassy Mountain bears today.

Western Canadian Collieries Ltd. sold its holdings in the Blairmore area to Western Canadian Mineral Holdings Ltd. in 1964 who in turn sold the property to Scurry Rainbow Oil Ltd. in 1966. Neither of the new owners carried out mining activities. Consol acquired the property in 1973 and since 1975 has shown an interest towards extracting coal from within Grassy Mountain.

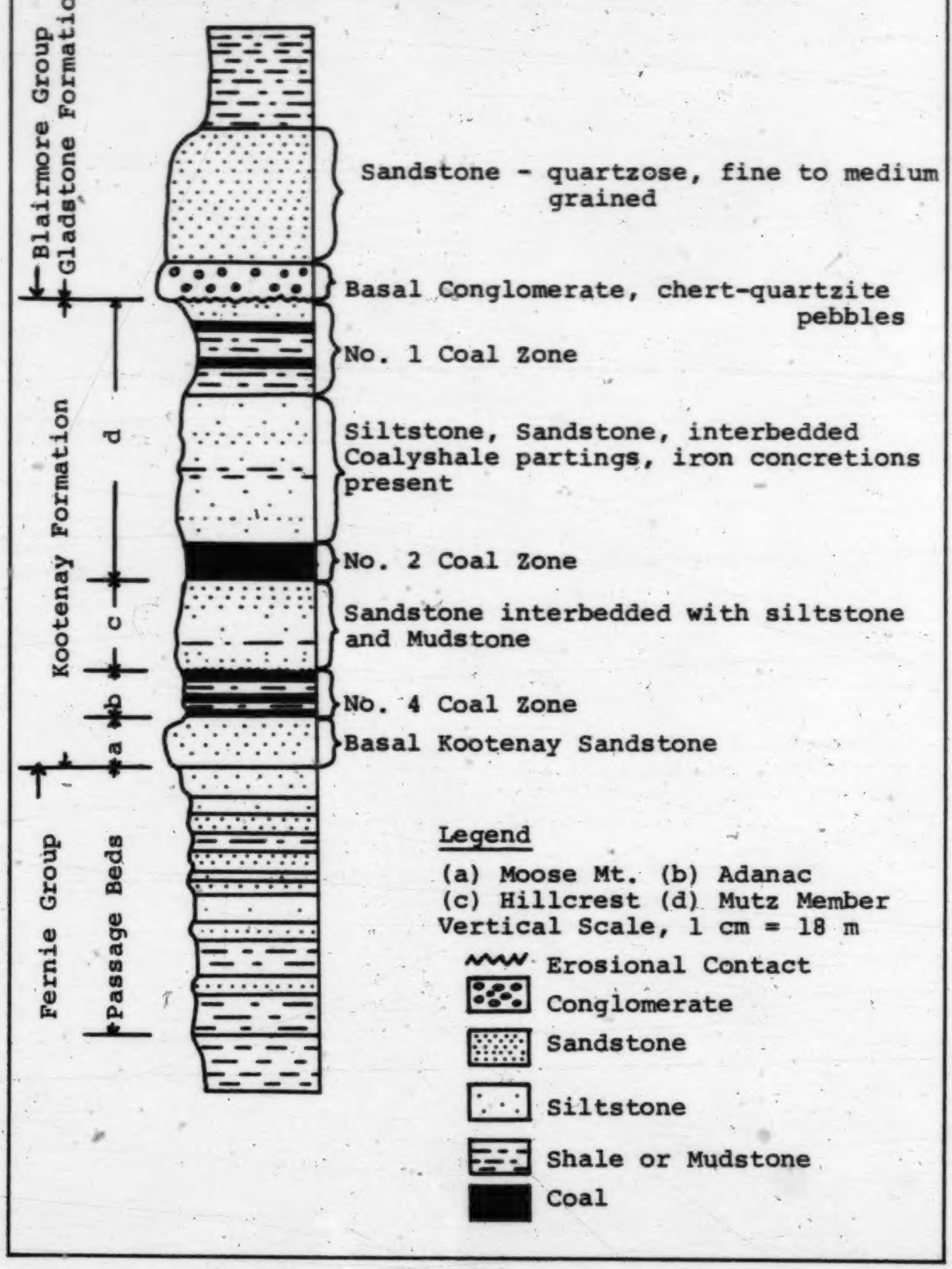
2.3 Geology

Deformations of Grassy Mountain's strata have resulted from compressional mountain building forces associated with the Laramide Orgeny. This has complicated the structural geology by producing numerous thrust faults and folds particularly within less competent horizons. Coal bearing strata strike a 005° and generally dip westward at about 30° with maximum dips of 60°. Movement along a major west dipping thrust fault within Grassy Mountain has resulted in repetition of coal measures. Folding association with this faulting often produced structural thickening of coal beds.

Coal within Grassy Mountain is contained in the deltaic late Jurassic to early Lower Cretaceous Kootenay Formation. At this location, the Formation is 125 metres thick and consists of mudstone, sandstone, siltstone and coal with numerous iron concretions. The Kootenay Formation lies conformably on recessive marine clastics of the Fernie Group and is bounded above by a disconformity consisting of alluvial clastic sediments of the Lower Cretaceous Blairmore Group. (Norris, 1959[49]; Rapson, 1964[58]; Consol, 1975[11]). (Fig 2.1)

Fernie Group exposures on Grassy Mountain are sparse due to their recessive nature. Upper beds of the Fernie Group consist of more resistant sandstones and siltstones which can be differentiated from overlying Kootenay strata by their deeper brown colored sandstones, decreased carbonaceous and mica content and an increase in limonite.

Fig 2.1 Generalized Lithostratigraphy of the Kootenay Formation and Bounding Strata, Grassy Mountain


Blairmore Group
Gladstone Formation
Kootenay Formation
Fernie Group
Passage Beds
d
c
b
a
Sandstone - quartzose, fine to medium grained
Basal Conglomerate, chert-quartzite pebbles
No. 1 Coal Zone
Siltstone, Sandstone, interbedded Coalyshale partings, iron concretions present
No. 2 Coal Zone
Sandstone interbedded with siltstone and Mudstone
No. 4 Coal Zone
Basal Kootenay Sandstone
Legend
(a) Moose Mt. (b) Adanac
(c) Hillcrest (d) Mutz Member
Vertical Scale, 1 cm = 18 m
Erosional Contact
Conglomerate
Sandstone
Siltstone
Shale or Mudstone
Coal

The Blairmore Group is subdivided into three formations, (from base) Gladstone, Beaver Mines and Mill Creek Formation (Mellow, 1967[47]; Consol, 1975[11]) At the Gladstone's base lies a distinctive resistant chert and quartzite pebble conglomerate unit varying from 5 to 10 meters thick, sharply contrasting with coaly sandstones of the upper Kootenay Formation. Above this conglomerate lies 30 metres of quartzose, cherty medium grained sandstones which are overlain by 30 metres of dark grey, calcareous shale and minor limestone. These sediments form the Gladstone Formation and are overlain by 300 metres of interbedded non-marine sandstones, siltstones and shales of the Beaver Mines Formation. Sandstones within this unit are rich in feldspars, contain volcanic debris and have a chlorite cement unlike quartzose sandstones of the Gladstone Formation.

At the thesis study location the Kootenay Formation contains 3 coalbearing horizons referred to as (from base) #4. #2, #1 zones. The #4 zone consisting of 2 or more seams over a 10-25 meter stratigraphic interval may contain up to 10 meters of coal. The #2 seam lies approximately 30 metres above the #4 seam and the single coal seam ranges from 10 to 35 metres thick. The #1 zone near the top of the Kootenay Formation is commonly represented by 2 or more seams spread over a 10-20 meter interval containing a maximum combined coal thickness of 4 metres.

The Kootenay Formation at its type section consists of the following Members and lithologies (Norris, 1959). The Moose Mountain Member lying conformably upon Fernie Group sediments consists of fine to medium grained, slightly calcareous, quartzose sandstones. Adanac sediments overlie the Moose Mountain Member and are equivalent to the #4 coal zone. Next, the Hillcrest Member composed of slightly calcareous sandstones and mudstones forms the interval between the base of the #2 seam and top of the #4 coal zone. The Mutz Member lying conformably upon the Hillcrest completes the Kootenay Formation. At its base lies the #2 coal seam. The remaining 58 meters of Mutz Sediments consist of interbedded siltstones, carbonaceous shales and mudstones, medium grained sandstones, several bands of iron concretions and thin coal seams from the #1 zone. This Member often forms open pit highwalls as the number 2 seam located at its base was the principal coal seam mined during 1947-1960. Material from the Mutz Member therefore comprises the bulk of overburden with spoil piles at Grassy Mountain. A detailed section of part of the Mutz Member was prepared for this thesis from data collected during field research. (Fig. 4.1, Appendix 2)

2.4 Surficial Geology

Surficial Geology within the study area primarily consists of 2 types of material, 1) Previously disturbed Mutz Sediments (overburden) which forms the bulk of spoil piles, 2) Glacial till. A few small fen deposits exist within the study area. Glacial till ranges from 0-10 metres in thickness and is composed of lithologies representing local underlying bedrock as well as carbonates and volcanics derived from sources a few kilometers to the west.

2.5 Soils

Soils in the Grassy Mountain have been classified by Consolidated Coal Company of Canada using the Canadian Soil Classification System (National Soil Survey Committee of Canada, 1968, revised 1974)[48]. Within the study area soils were found to be mainly Brunisolic and Regosolic Orders with patches of Gleysolic Order soils in poorly drained depressions and Lithosolic soils present on steep mountain slopes. Most soils have developed upon sedimentary rocks glacial tills, minor alluvium and coarse outwash deposits. The lower slopes of Grassy Mountain are mantled under a till veneer which is predominantly loam to clay loam with a high proportion of silt due to the influence of loess which blankets the area. Sandstones, siltstones, shales and coal are the parent materials which have yielded Lithosolic soils upon the mountain slopes. These soils, where developed, are generally thin, possessing a sandy to sandy loam texture.

2.6 Climate of the Area

Climate conditions existing within the thesis area must be fully understood in order to correlate information concerning products and weathering rates resulting from natural and artificial weathering processes. Weather recording devices were located at Grassy Mountain for only short periods (August, 1974 - November, Consol, 1975). Much of the climatic conditions are therefore extrapolated from nearby weather recording stations, ie. Cowly, Coleman, Lundbreck and Ironstone fire lookout which have respective elevations of 1170 meters, 1340 metres, 1180 metres, and 2070 metres (Map 2). The Ironstone station, located at a similar elevation to Grassy Mountain's summit provides valuable data which may be directly applied to Grassy Mountain. Detailed climatic records for the five locations are listed in Table A1-A4 and B1-B6 of Appendix 1.

2.7 Air Masses

Grassy Mountain lies between 1280 metres and 2070 metres a.s.l. within an area which experiences frequent rapid movements of warm moist Pacific are (chinooks). These chinooks cause enormous fluctuations in winter temperatures, increased snowfalls and rapid periodical removal of snow packs. Elevation variations also strongly affect the local climatic patterns, ie. adiabatic loss of 5-9.8°C per kilometer of increased elevation (Koeppe, C.E. et al; 1958[31]). The weather of this area is characterized by cold winters followed by short, hot summers. The mean January temperature is -11°C while the July mean temperature rises to +11.0°C. The transitional period of spring and fall vary in length but usually last for several months. Grassy Mountain receives approximately 640 millimetres of precipitation per year of which one-third to one-half falls as snow. Frequent chinooks, low rainfall and high potential evaporation result in this area experiencing a moisture deficit (Longly, 1972[39]; F. F. Slaney and Company for Consol, 1975[11]).

2.8 Temperature

Temperatures at Grassy Mountain were monitored using a Mechanical Weather Station from August 18, 1974 to November 1975. (Consol, 1975)[11] At higher elevations in the area it is possible to experience frost every month of the year. (Appendix 1 Table A-4) Mean monthly temperatures generally remain below freezing from November to March within the study area but extreme minimum and maximum tables indicate the possibility of each month experiencing plus Celcius readings, a phenomenon associated with chinooks. (Appendix 1, Tables A1-A3) Continuous frost free days generally begin in mid June and continue until late August. (Environment Canada, 1941-1970; Normals, Vol 1, Temperature, 1973)[18]

Spring starts around the beginning of May at Grassy Mountain. Snowmelt begins at this time with maximum melting occurring in early June resulting in spring runoff which is greatly controlled by chinook winds. When chinooks are frequent during spring melt a great deal of moisture is lost by evaporation, resulting in less water available for runoff or infiltration into overburden spoil piles.

Summer occurs during June, July and August and snow can usually be found persisting well into these months as evening temperatures may fall below zero while mean daily temperatures may be in the $+15^{\circ}C-+25^{\circ}C$ range. July is the only month at which the higher elevations are free of frost. (Appendix 1 Table A-4)

Frost appears at Grassy Mountain between August 15 and September 15.

Root, (1976)[60] examined and noted the climate characteristics of an unreclaimed abandoned strip mine near Cadomin, Alberta. Climatic data of the minesite varied little from surrounding vegetated areas, air temperatures over the minesite being generally 1-3°C higher. Ground surface temperatures of spoil piles were often in excess of 50°C during warm summer days and were much higher than vegetated areas. Harrison, 1972, noted similar surface temperatures for spoils in the Crowsnest region.

Temperature calculations (Appendix 1 Tables A-1 to A-4) were based upon Koeppes' and Barry's 5-9, 8°C decrease in temperature per kilometer increase in elevation. These temperatures will become part of the calculations used in predicting the increased rate of weathering generated by artificial soxhlet weathering.

2.9 Precipitation

Precipitation records for this region indicate an increasing trend through spring time reaching a maximum in June. The thirty year annual mean precipitation for this area is 640 millimeters of which 40% falls within summer months as rain, 10-25% falls as rain within spring and autumn period and 35-50% falls as snow during the winter months. Precipitation fluctuations from year to year vary considerably, ie: Coleman 1971 had 800 millimeters, Coleman 1972 had 650 millimeters. (Appendix 1 Tables B-1 - B-3)

(Environment Canada 20 year pattern, 1973)[18] Most of the summer rainfall occurs as intense short downfalls, ie: thunderstorms, resulting in only a few days per month receiving rainfall. Spring and fall period of rains may be of longer duration lasting several days with gentle precipitation. (Appendix 1 Tables B-4 - B-6)

It is critical to observe the occurrence of precipitation with respect to temperature. Nearly all the precipitation infiltrating the ground or running off occurs during the four month period of warmer spring-summer temperatures.

2.10 Wind

Wind was monitored at Grassy Mountain at an elevation of 1674 metres using a Mechanical Weather Station MRI Model 1071 which records wind distribution, speed and temperature 7 metres above the ground surface (Consol 1975). Winds during this period were predominately from the west and southwest. Several calm periods were recorded which resulted in variations of mean daily wind speeds ranging from 10 km/hr in August to 11 km/hr in September. A maximum hourly mean speed of 43 km/hr was recorded on September 8, 1975. Boulder pavement observed on level areas of overburden at Grassy Mountain may be indicative of periods of relatively high velocity winds. Root (1976)[60] observed boulder pavement on overburden at an abandoned open pit mine near Cadomin and from the size of particles transposted he calculated wind velocities to be in the order of 160 km/hr.

This figure is supported by a reported maximum wind velocity of 160 km/hr during the winter 1972-73 (Edmonton Journal, 1973)[16]. Wind speeds over open areas within major mountain passes often attain velocities resulting in physical abrasion and transportation of unreclaimed overburden.

CHAPTER 3

WEATHERING OF ROCKS AND MINERALS

"Weathering", as defined by Buckman and Brady (1967)[6], "is a combination of destruction and synthesis". Minerals undergoing weathering forces are in an environment quite unlike the higher temperatures and pressures in which they are formed. Their response to the situation of disequilibrium is to change to more stable forms. This is achieved by mineralogical, chemical and grain size alterations. These changes resulting from either physical and/or chemical weathering are accompanied by a release of soluble constituents, most of which are lost in drainage waters. In nature the processes of physical and chemical weathering virtually always occur together so that they often become indistinguishable.

3.1 Environmental Factors Influencing Weathering

Jenny (1951)[29] considered five fundamental variables as being responsible for rock weathering: climate, parent material, biological activity, topography and time. A sixth factor which is of local significance is man's activity, ie. open pit mining.

3.1.A Climate

Climate, the sum of all weather which occurs at a location, is considered the most important factor in rock weathering. (Birkeland, 1974[3]; Carrol, 1970[9]). Moisture and temperature dominate the climate's tools for weathering. Precipitation supplies moisture which is involved in most physical, chemical and biological weathering processes, supplying a medium for reactions to occur and a method of removal for soluble products of weathering. Temperature influences the rate of chemical reactions as well as physical disintegration of rock. Generally Van't Hoffs' temperature rule, which states, "a rise of ten degrees celcius doubles or triples the rate at which a chemical reaction occurs", is accepted in most weathering studies.

Peltier (1950)[54], Ollier and Boyd (1969)[50] have studied the effects of temperature and moisture upon chemical and physical weathering processes. Given a specific climatic environment with respect to precipitation and temperature, they could predict the intensity and process of rock weathering most likely to occur. (Fig. 3.1)(Loughnan, 1973)[42], mentions that it is not so much the total rainfall which governs the rate of weathering but rather the amount of precipitation which actually infiltrates the weathering zone, percolates through the rock carrying dissolved components, eventually emerging into streams and lakes.

Strakhov (1967)[62] found that higher temperatures, increased moisture and organic matter comparable to tropical areas resulted in weathering rates 20-40 times greater than those experienced in temperate latitudes.

Arid areas experiencing greater evaporation than rainfall experience minor rock weathering. Cold polar climates experience little or no chemical alterations. Here physical disintegration of rock material occurs as a result of frost shattering. Thus weathering dependant upon moisture will most likely be at a maximum where it is evenly distributed, occurring as gently persistent showers and at a minimum where precipitation is seasonal and restricted to short intense downpours, ie. Grassy Mountain.

Although the importance of temperature and precipitation cannot be overstressed, other climatic factors may be significant. Wind may be of local importance where surface materials are exposed to air as they are in open pit spoil sites. Wind will increase the rate of evaporation resulting in a moisture loss, thereby decreasing chances for chemical weathering. This drying effect may result in increased physical disintegration by the process of wetting and drying. Where strong winds occur physical abrasion and particle breakdown caused by wind-borne particles may occur.

3.1.B Parent Material

Characteristics of parent material such as variations in its mineralogy, texture and structure strongly influence weathering rates.

Ollier (1969)[52] compared porosities and permeabilities of several rock types. Ollier found that porosity may vary by a factor of 18 whereas permeability varied up to 500 times (Table 5, Appendix 5). Parent material which exhibit high porosity and permeabilities are more susceptible to weathering as more minerals are exposed to fresh water which can replace and remove solutions containing dissolved products of weathering. Birkeland (1974)[3] and Carroll (1970)[9] noted that coarser grained rocks in tills exhibited a greater degree of weathering than did finer grained rocks of similar composition within the same till.

Mineral stability is extremely important when considering parent material. Each mineral's response to its out of equilibrium situation at the earth's surface is unique. Goldich (1938)[22] pioneered the area of mineral stability in his classic study of rock weathering. He noted that the weathering sequence for common silicate minerals coincides exactly with Bowens (1928)[4] reaction series of crystallization for a silicate melt. Minerals first to crystallize out of the silicate melt, ie. olivine, are less resistant to weathering than those last to crystallize, ie. quartz. Several scientists have confirmed Goldich's findings: Pettijohn (1941)[55], Marshall (1964)[43], Pedro (1960)[53], Loughnan (1962)[40].

Resistance to weathering exhibited by each mineral is largely a function of mineral structure. Hay (1959)[27] and Keller (1954)[30] noted that an increased sharing of oxygens between adjacent silicon tetrahedra correlates with increased resistance to weathering. Keller suggests that bond energies explained observed weathering sequences. Mineral breakdown during weathering is initiated at the sites of the weakest bonds. Silicon-Oxygen bonds, ie. quarts, being the strongest, most resistance, while common base ion-oxygen bonds, ie. olivine, being the weakest.

Birkeland's (1974)[3] observations of tills in the Sierra Nevada yielded the following series of igneous rock's resistance to weathering: gabbro-granite-rhyolite. These observations support the findings of Goldich and Keller.

There is no hard and fast rule for determining which sedimentary rocks are most susceptible to weathering. Some

Some sedimentary rocks weather more quickly than igneous rocks but in many instances the reverse trend is observed. Although the number of minerals found in sedimentary rocks is large, only a few, ie. quartz, feldspar, calcite, dolomite and clay minerals, constitute the majority of sedimentary minerals, (Mason, 1966)[45]. Since clastic sedimentary rocks are by-products of former weathering their mineral composition contain higher proportions of resistant minerals than their sources. This trend would indicate that mature clastic sediments would be highly resistant to weathering. (Pettijohn, 1941[55]).

Clay content and cementing agents of sedimentary rocks strongly influence their resistance to weathering. Rocks containing large contents of clay may disintergrate more rapidly than rocks with less clay minerals. This is because clays expand and contract with moisture variation. Each cementing agent also has its own characteristic solubility and resistance to weathering, ie. quartz cement is generally much less soluble than calcite cement.

Carbonate minerals in or as sedimentary rocks have not been included in Goldich's mineral stability series. Weathering of these minerals are largely controlled by carbonate equilibria. This will be discussed in detail later in this chapter as its importance is significant to this research.

Turekin and Wedephl (1961)[66] compared the average elemental composition of several rock types representing various parent material. (Table 3:1). Their observations provide a guide which may be useful in predicting which specific elements may be liberated upon rock weathering.

Table 3.1

Abundance of Certain Elements Present in Rocks
(Concentration ppm)

Element	Rock Type			
	Shale	Sandstone	Carbonate	Igneous Rock
Na	9600	3300	400	28300*
Mg	15000	7000	47000*	20900
K	26600*	10700	2700	25900
Ca	22100	39100	302300*	36300
Si	73000	368000*	24000	277200
Fe	47200	9800	3800	50000*
Mn	850	1.0	1100*	950
Cu	45	1.0	4	55*
Al	80000	25000	4200	81300*
Pb	20*	7	9	13
Zn	95*	16	20	70
Ni	68	2	20	75*

* Rock species containing highest content of a specific element

Source: Turekian and Wadelohl, Bull. Geol. Soc. Am. 72, page 175, 1961.

3.1.C Topography

Topography influences the rate of chemical weathering and the nature of the weathered products in several ways. Topography controls: (Loughnan, F.C., 1973[42], Ollier, 1969[52])

(a) the rate of surface water runoff and therefore the rate of moisture intake by parent materials.

(b) the rate of subsurface drainage which controls leaching rates of soluble constituents.

(c) the rate of erosion of weathered products and thereby the rate of exposure of fresh mineral surfaces.

(d) aspect which locally controls variations in temperatures affecting both chemical and mechanical rock disintegration.

Steep slopes quickly shed rain waters resulting in few chemical alterations but greater rock weathering by mechanical disintegration.

Flat low lying areas promote infiltration of moisture, sluggish drainage, and a buildup of soluble products, which inhibits further breakdown and alteration of parent materials. This environment results in waters becoming distinctly alkaline if parent materials are rich in alkalies or strongly acidic where organic matter has accumulated.

The ideal topography which promotes chemical weathering is one of rolling or gently sloping uplands where surface runoff is low and subsurface drainage unimpeded. (Loughnan, 1969)[41] This ideal topographic situation exists on spoil piles at Grassy Mountain.

Topography influences physical and chemical weathering by locally influencing the quantity of moisture received and retained and the temperature at which weathering processes occur.

3.1.D Biological Activity

Biological activity may play an important role towards rock weathering and soil formation. Soil Microorganisms' abundances are restricted by certain conditions summarized below by Corbet (1933) and Weyer (1980):

(a) Temperature - the optimum is between 25-37°C but the range which species may exist lies between 10-45°C.

(b) Moisture - for most species (aerobic) moisture must be between 50% and 70% saturation value which is also the optimum range for plant growth.

(c) Depth - practically no organisms exist below the level of soil humic matter.

Harsh conditions at Grassy Mountain have retarded plant development and would restrict soil microorganisms, therefore biological weathering would be considered of minor importance.

3.1.E Time

Jenny's fifth factor, time, is the least predictable. At best a relative estimate of time is used to determine its role in rock weathering and soil development. Although weathering in nature proceeds slowly it is noticable over man's lifetime or preserved on material whose age can be calculated.

Several methods for determining duration or rates of rock weathering have been developed and employed over the last

100 years. Some of these are listed below:

(1) Study and recording of weather rind thicknesses on boulders, tombstones, pyramids, or older parent material which have been exposed to weathering for a known period of time. (Birkeland, P., 1974[3]; Ollier, C.D., 1969[52]; Jenny, H., 1951[29])

(2) Clay content of soil, usually increases with time of weathering provided that the parent material contains minerals capable of being converted to clays. (Birkeland, P., 1974[3]; Carrol, D., 1970[9])

(3) Examination of waters draining an area which is undergoing rock weathering. (Lineuf and Aubert, 1960[37]; Sweeting, 1966[65]; Jackson 1977-1978[28])

(4) Chemical analyses of fresh parent material compared to that of weathered material. (Riech, 1943)[59]

Each method requires knowledge pertaining to the other factors which have resulted in rock weathering. Caution must be used to insure correlations of similar conditions and materials for each time indicator employed. Climatic conditions under which weathering occurs today may be vastly different from those under which it was initiated.

It is generally accepted that weathering rates occur most rapidly at the initial stages of weathering and become increasingly slower as soils mature. (Birkeland, 1974)[3] Ollier, C.D. (1969)[32] found "weathering rinds on basalts thicken at a decreasing rate and the formula relating thickness to time is logarithmic."

3.1.F Man's Activity

Man's activities, although recent in terms of geologic time, have become a significant factor on a global scale. Open pit mining operations alone have resulted in the break up and displacement of millions of cubic metres of rock per year. Man's greatest influence in weathering is the physical destruction of rocks and minerals. Accelerated physical breakdown of parent material increases: (a) the surface area of rock allowing additional sites for chemical weathering to occur; (b) the porosity and permeability of the overburden. (Birkeland, P., 1974[3]; Carrol, D., 1970[9]) Man therefore directly accelerates rates of physical weathering and both indirectly and directly accelerates chemical weathering.

All factors considered, it may be possible to predict which weathering process will dominate and the relative time necessary to "stabilize" a parent material in its new environment. Carrol (1970)[9] summarizes weathering as a complex chemical process which is intimately associated with physical processes and environmental factors. This chemical reaction is written as:
(Atmosphere + Biosphere + Hydrosphere) + Lithosphere = weathered lithosphere + residual minerals + dissolved chemical elements
Its intensity varies with Jenny's five factors and man's activity.

3.2 Weathering Processes

Mechanical and chemical processes are responsible for most rock and mineral weathering. The chemical and physical weathering processes discussed in this section deal specifically with those processes relevant to the research area.

3.2.A Physical Processes

Physical weathering occurs when solid rock is broken into fragements with little or no chemical alteration. Very cold, dry or very hot, dry climates result in only physical weathering occurring.

The mechanism responsible for all processes of physical weathering is sufficient stress within the rock causing it to break. Physical breakdown of sedimentary rocks is enhanced by the following parent material characteristics, fractures and joints, bedding plains and laminations, grain size and composition, cement composition, porosity and permeability.

Parent material is important physically as a source of the skeletal material of a soil. Krumbien and Tisdel (1940)[35] showed that the size distribution of artificially crushed stone and the grain size distribution of disintegrated sedimentary rock is similar to that of the original sediment.

3.2.A.1 Frost Action

Upon freezing at 0°C, water volume increases 9% exerting a pressure upon the walls of its confinement. This ice pressure rapidly increases with decreasing temperature to about -22°C where a pressure of 2115 atm. is attained. This pressure exceeds the compressive strength of most rocks therefore resulting in their disintegration. (Winkler, 1975)[71]

A rock's susceptibility to frost damage is related to porosity, critical saturation, critical mean pore size and continuity of pores. A critical mean pore size of 5 microns renders a stone frost susceptible. Rocks with larger mean pore diameters are less sensitive to frost and physical disintegration than rocks with small mean pore sizes. Fine-grained rocks which have absorbed water in vacuum capillaries are generally very susceptible to frost when they are above 5% but are durable below 1% water absorption. (Walker, 1965[67]; Winkler, 1975[71])

Stone disruption by frost action is explained by:

(a) Volume increase during the change of water to ice.

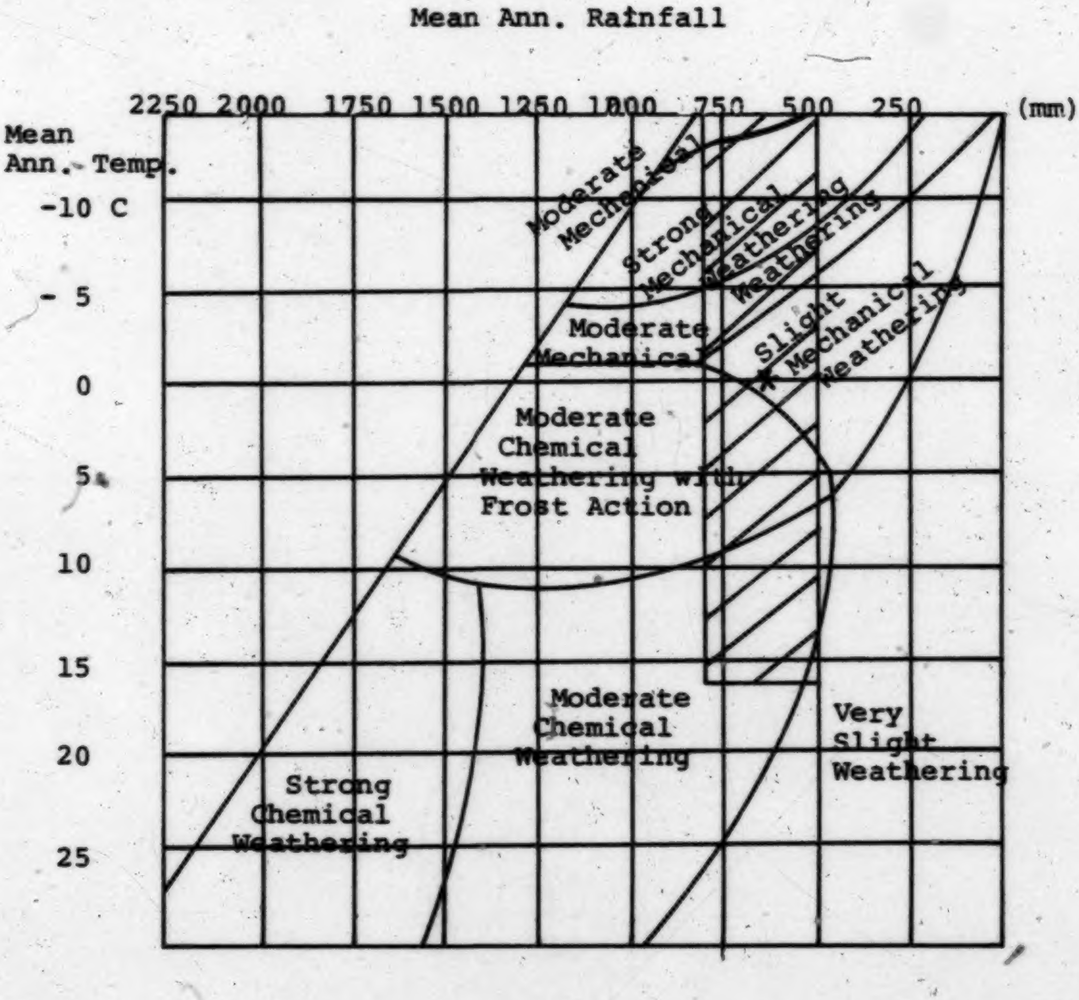
(b) Displacement of pore water from advancing frost fronts. (Power, 1955)[57]

(c) Conversion of pore water to ordered water by clay minerals and other negatively charged sites. (Dunn and Hudu, 1975)[15]

(d) Volume increase in unfrozen water at temperatures below 0°C. (Larson and Cady, 1969)[36]

Peltier (1950)[54] devised a means of determining the intensity of frost action from knowing conditions of temperature and precipitation of a particular environment. (Fig. 3.1 and Fig. 1 and 2, Appendix 3) Two minima occur, (a) where conditions are too warm for freezing to occur, or (b) areas too cold for thawing to occur. The frequency of freeze-thaw cycles is of paramount importance. Regions which experience long transitional periods between seasons too cold for thawing and too warm for freezing will experience the greatest intensity of frost weathering.

Fig.3:1 Variations in Types of Weathering with Variations in Temperature and Precipitation



(Modified after Peltier, 1950) Olller C.D., Weathering; Oliver and Boyd 1969.

* Weathering Conditions at Grassy Mountain. (Normals) ✳
(Range) ▨

3.2.A.2 Salt Crystal Growth

Solutions emerging from rocks and evaporating at their surfaces often precipitate salts; ie. $CaCO_3$, $CaSO_4$, Weyer (1980)[69]. This crystallization process especially in fractures or pores at the rock's surface may lead to granular disintegration. (Ollier, 1965)[51]

3.2.A.3 Expansion Resulting From Chemical Alteration

During chemical alteration of minerals and rocks a change in volume often occurs, the weathered product often having a greater volume than the original. This expansion gives rise to physical alterations such as exfoliation, fractures radiating out from expanded mineral and a granular rather than flaky rock breakdown.

3.2.A.4 Insolation Weathering

Griggs (1936) demonstrated that heating and cooling of rocks and minerals alone had little effect on rock disintegration unless water was also present. It is therefore generally accepted that insolation weathering is of minor importance to physical weathering.

3.2.A.5 Wetting and Drying

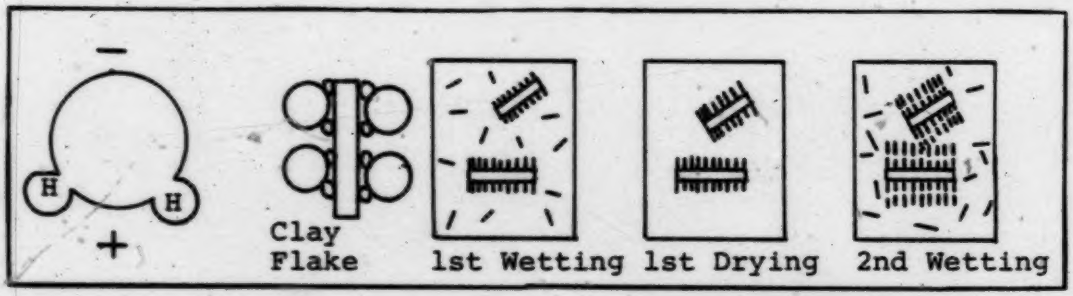
This process of mechanical disintegration of rock is very significant. Fine-grained rocks however show greater disintegration than coarse-grained (sandstone-siltstone) when subjected to similar wetting-drying conditions.

Two types of rock disintegration occur as a result of wetting and drying;

(a) surface flaking of rock particles.

(b) major splitting of samples along planes of weakness such as fractures, joints, cleavages, beddings, etc. Samples prone to this type of weathering show visible flakes after five cycles and almost total original surface destruction after 180 wetting-drying cycles. (Ollier, 1965)[51] An explanation of this process considers the mechanism of "ordered water" molecular pressure. Water, a polar liquid, orientates itself so that positively charged hydrogens attach themselves to negatively charged clay or mineral surfaces. Other water molecules attach to these molecules' surfaces joining negative ends to form numerous tiny bar magnets. (Fig. 3.2)

Fig. 3.2



Repeated wetting and drying allows water molecules to become increasingly ordered assuming a quasi-crystalline nature and exerting expansive forces which thrust against confining walls thereby resulting in rock shattering.

3.2.A.6 Man's Effect Upon Mechanical Disintegration

This weathering process is responsible for the initial physical disintegration of rocks removed by such operations as open pit coal mines and sets a pace for natural physical and chemical weathering to occur. Blasting results in fracturing materials to particles which can be easily handled.

Decreasing particle sizes as a result of physical disintegration intensifies further physical breakdown as well as chemical weathering. (Fig. 3.3) from Birkeland (1974) after Blake illustrates how surface area and number of particles increase within a given mass as grain size decreases. This phenomenon is extremely important and is one of the fundamentals of physical and chemical weathering of rocks. Chemical weathering depends upon mineral surface contact. Increasing surface area through physical disintegration of rock provides additional reaction sites for chemical alterations to occur.

3.2.B Chemical Weathering

Chemical weathering involves a series of surface chemical reactions between parent material, the atmosphere and water. It is a chemical process whereby minerals in out of equilibrium environments respond to leaching water at low temperatures, usually 30°C or less, and atmosphere pressures ranging from sea level to the highest mountains. The final products of chemical weathering are oxidized, synthesized, resistant secondary minerals and chemical solutions containing soluble chemical elements of the original rock. (Fig. 3.4) (H. O. Buckman, Fields and Swindle, 1965[6]; Carroll, 1970[9]; Loughnan, 1969[41]) Carroll (1970)[9] represents chemical weathering by the following reaction:

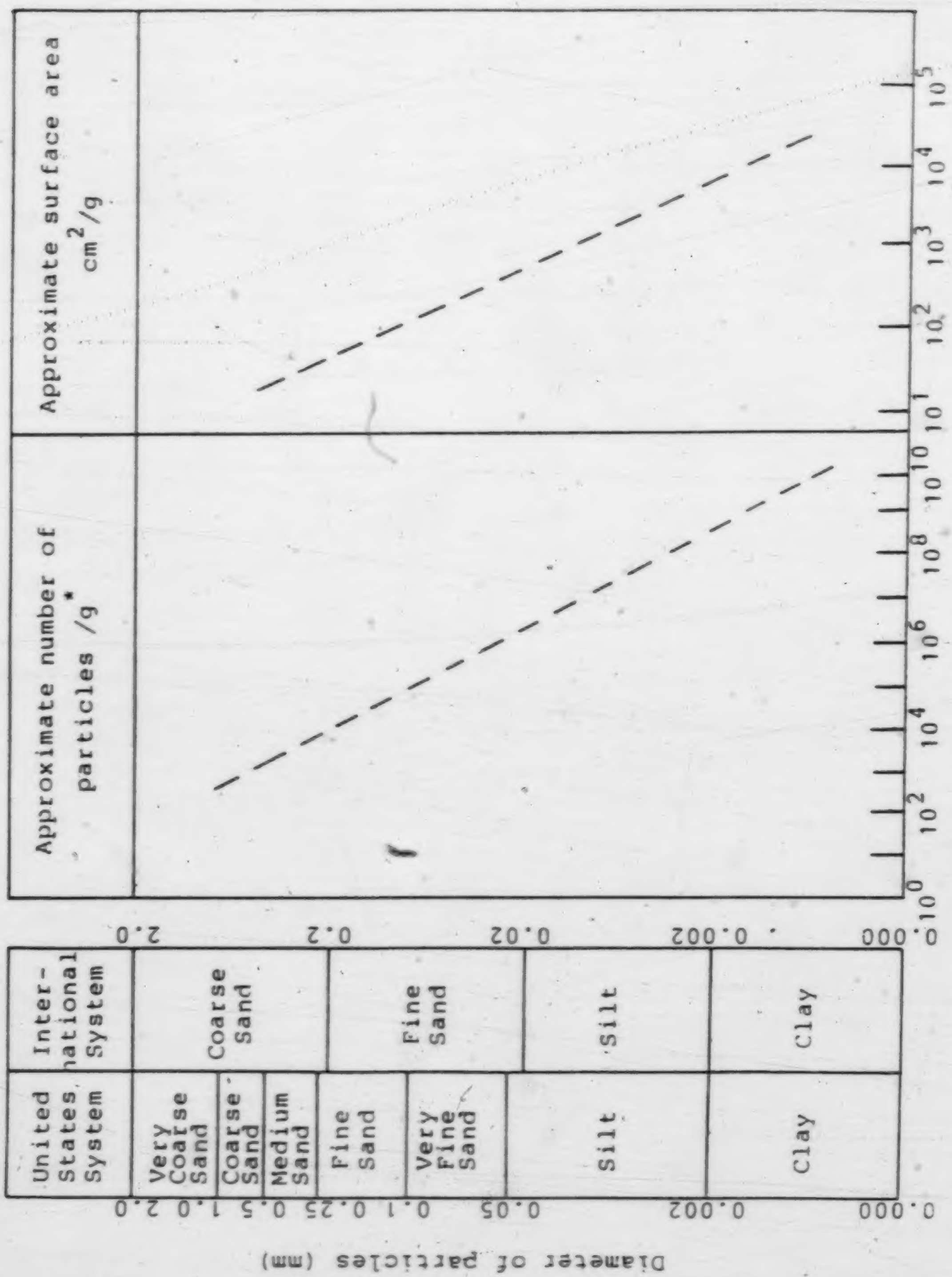


Fig. 3.3 Particle Size Classes Frequently used in Pedology

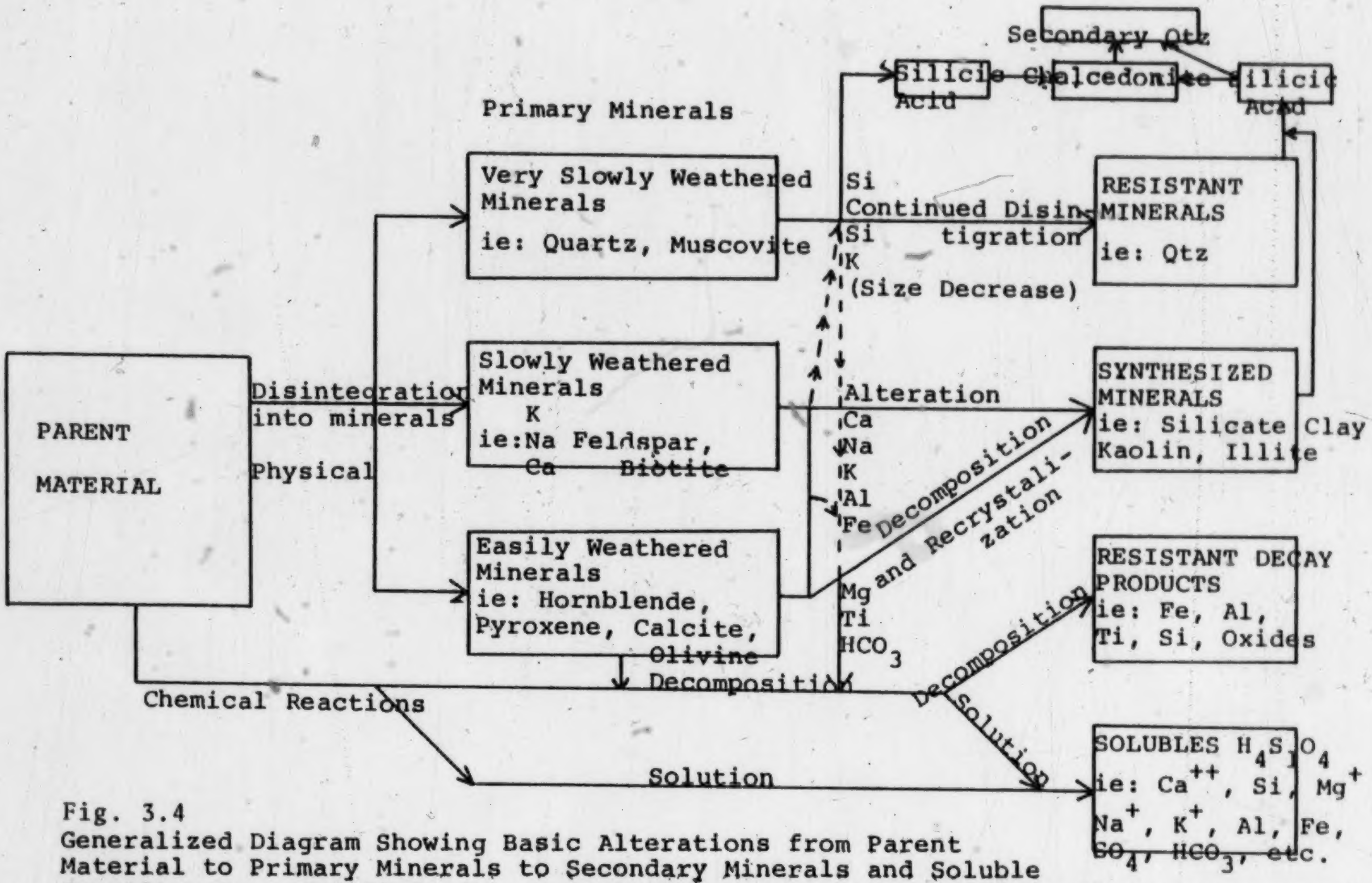

Primary Minerals
PARENT MATERIAL
Disintegration into minerals
Physical
Chemical Reactions
Very Slowly Weathered Minerals ie: Quartz, Muscovite
Slowly Weathered Minerals ie:Na K Ca Feldspar, Biotite
Easily Weathered Minerals ie: Hornblende, Pyroxene, Calcite, Olivine
Decomposition
Solution
Si
Continued Disintigration
Si
K
(Size Decrease)
Alteration
Ca
Na
K
Al
Fe
Mg
Ti
HCO3
Decomposition and Recrystalization
Decomposition
Solution
Silicic Acid
Chalcedonite
Secondary Qtz
Silicic Acid
RESISTANT MINERALS ie: Qtz
SYNTHESIZED MINERALS ie: Silicate Clay Kaolin, Illite
RESISTANT DECAY PRODUCTS ie: Fe, Al, Ti, Si, Oxides
SOLUBLES H4SiO4 ie: Ca++, Si, Mg+ Na+, K+, Al, Fe, SO4, HCO3, etc.

Fig. 3.4
Generalized Diagram Showing Basic Alterations from Parent Material to Primary Minerals to Secondary Minerals and Soluble Constituents, Modified after H.O. Buckman and N.C. Brady, The Nature and Properties of Soils, p. 268, Macmillan Co., 1969 and Fields and Swindle, New Zealand J. Sci. Tech. 36B, p. 140, 1954.

$$\text{Rock} + \text{Oxygen} + \text{Water} + p\int_{\text{mountains}}^{\text{sea level}} = \begin{array}{l}\text{saprolite soil} + \\ \text{soluble inorganic} \\ \text{and organic ions} \\ \text{or compounds}\end{array}$$

In brief Loughnan describes three simultaneous processes which are involved during chemical weathering of silicate minerals:

(1) Breakdown of parent mineral structures with the concomitant release of cations and silica.

(2) The removal in solution of some of the released constituents.

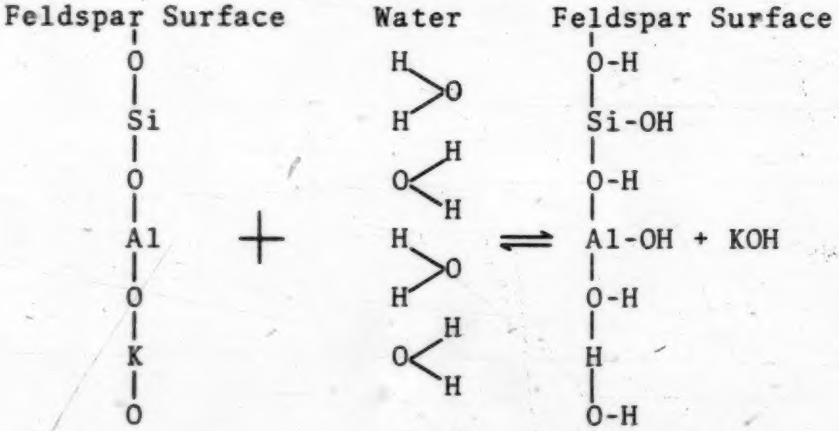
(3) The reconstitution of the residue with components from the atmosphere such as oxygen or carbon dioxide, to form new minerals which are in stable or metastable equilibrium with the environment.

Chemical weathering is by far the most important process of rock disintegration at the earth's surface.

3.2.B.1 Mechanism of Parent Material Breakdown

The simplest and usually initial reaction in chemical weathering is dissolving of soluble minerals in water. (Krauskoff, 1967[33]; Jenny, 1951[29]) Exposed atoms and ions at a mineral's surface possess unsatisfied valancies and when these sites are exposed to water, hydration may occur. Hydration often involves considerable volume changes and prepares the mineral for further alteration by other chemical processes. Attractive forces at the mineral's surface may be sufficient to polarize the water dipoles causing dissociation into hydrogen and hydroxyl ions, therefore permitting hydroxyl ions to bind to exposed cations while hydrogen ions may replace cations at the mineral's surface. The latter process results in a rise in the liquid's pH.

The following example employed by Jenny (1950)[29] describes the breakdown of a potassium feldspar.



Source: Loughnan, 1969.

This reaction removes potassium from the feldspars permitting aluminum to assume its preferred octahedral coordination. As potassium is released, a fine mica, sericite, may form, which is sometimes the first indication of feldspar alteration. (Carroll, 1970)[9] These processes thereby render surface layers to an unstable form and various polyhedra are then released into the sourrounding water. Initially polyhedra released may form amorphous colloids which later may become orientated into structures forming secondary material. (Tamm, 1930; Stevens and Carren, 1948[61]; Garrels and Howard, 1958[21]; Frederickson, 1951[20]; McConnel, 1951[46]) Stevens and Carren ground minerals in distilled water and carbonic acid and discovered that the decomposition of feldspars resulting in an increase in pH and the release of cations depended upon producing fresh mineral surfaces. Minerals containing alkalies yielded alkaline pH values while those without these ions produced acidic solutions. Each mineral was found to produce a specific pH (Mineral's abrasion pH) in the solution they were ground. Hydration, hydrolysis and hydrogen replacement continue with each mineral in solution until a state of equilibrium is reached.

Two important conclusions concerning parent material breakdown by chemical weathering are (Loughnan, 1969):

(1) Hydrogen ions produced by hydrolysis at a mineral's surface gain easy penetration into crystal lattices and their high charge-to-radius ratio produces a disruption effect on the charge balance within the lattice.

(2) The persistance of aluminum in a tetrahedral coordination and the retention of highly mobile cations in secondary mineral products indicates that a great deal of parent mineral structure is inherited by secondary products.

Weathering of silicates is therefore primarily a process of hydrolysis. Regardless of how a reaction proceeds, hydrolysis of silicates leaves a solution more basic than it was in its original state. Krauskoff (1967) noted this generalization holds for hot water at depth as well as cold water near the surface. "Any solution in contact with silicate minerals cannot long remain appreciably acid, and if contact is continued the solution must eventually become alkaline." (Krauskoff, 1967)[32]

3.2.B.2 Mobilities of Common Metallic Ions

As weathering proceeds, not all cations are taken into solution with the same ease. Some tend to be easily lost in waters whereas others become concentrated in a residue. The six most important factors governing ion mobilities are:

(1) pH of the solution
(2) Eh of the solution
(3) Ionic potential
(4) Oxidation
(5) Fixation of cations
(6) Leaching

3.2.B.3 Influence of pH and H ion Concentration upon Ion Mobilities

Mason (1952)[44] discovered that most natural waters affecting cation mobilities have pH values which normally lie between pH 4-9. Krauskoff (1967)[33], Carroll (1970)[9] and others support Mason's findings but add that local waters may experience pH values as low as 0 or as high as 10 or 11. Fig. 3.5 represents the solubilities of some important cations dealt with in this research. This figure indicates that within normal natural pH conditions $Ca(OH)_2$, $Mg(OH)_2$ and the alkalies (not shown) are completely soluble whereas $Fe(OH)_3$ and Al_2O_3 remain insoluble. The solubility of silica, as quartz is low and maintains a rather constant concentration of 2-6 ppm in normal waters, while amorphous silica is nearly 20 times as soluble as quartz. (Carroll, 1970)[9] The only components where the mobility is influenced by changes within normal environmental pH are $CaCO_3$ and $Fe(OH)_2$.

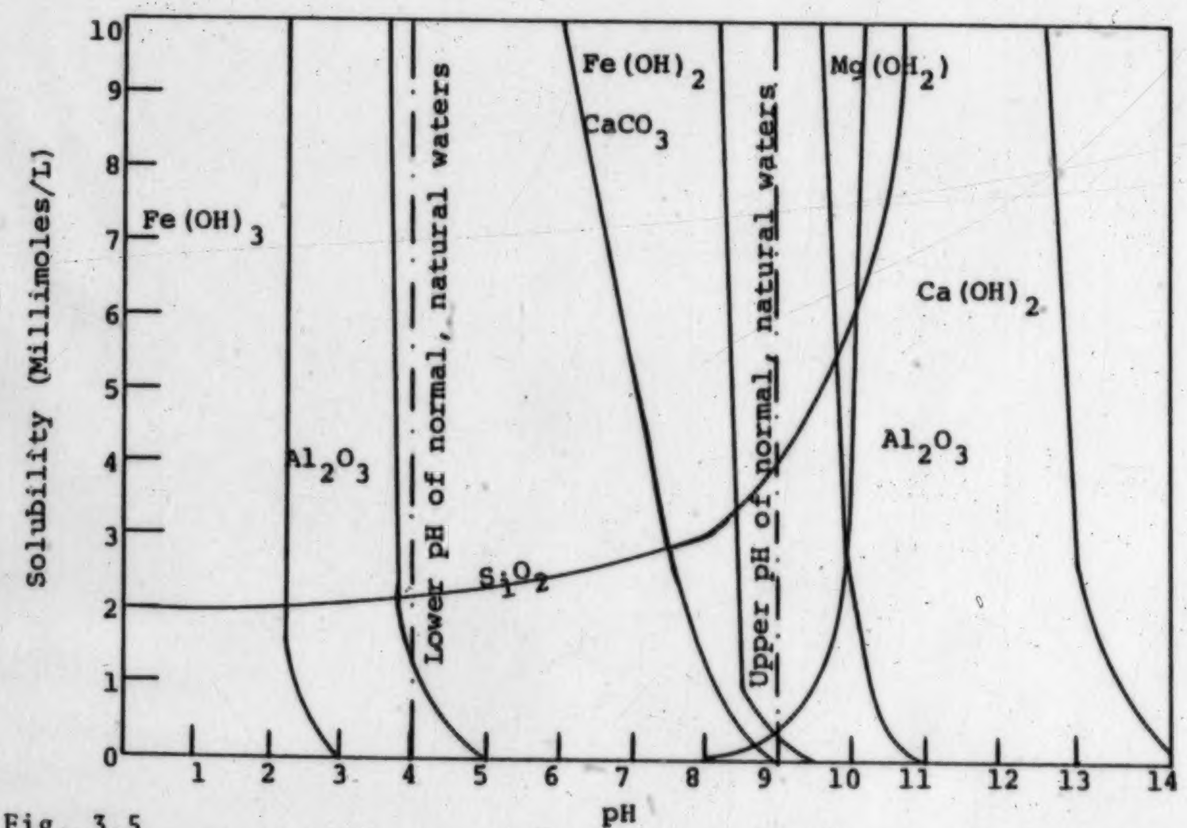


Fig. 3.5
Solubility in relation to pH for some components released during chemical weathering. According to Mason (1952) pH values of natural waters normally lie between 4 and 9. The alkalies, not shown here, are completly soluble within this range, $Fe(OH)_3$ and Al_2O_3 remain insoluble. The most pH-dependent components in natural environments are $CaCO_3$ and $Fe(OH)_2$. S_iO_2 refers to quartz. Source modified from Loughnan, 1973, p. 32 and Mason, 1966, p. 167. Carrol, 1970, p. 100.

Within normal natural waters constituents are observed to be lost in an orderly fashion. Polynov (1937) and Miller (1961) observed the following loss of constituents within rivers draining igneous and sandstone rocks:

Igneous rock Ca^{++} Na^{+} Mg^{++} K^{+} SiO_2 Fe_2 O_3 Al_2O_3
Sandstone Ca^{++} Na^{+} K Si = Al

Their findings coincide well with minerals' resistance to weathering.

Acidity (pH) plays a paramount role in rock weathering. Variations in pH are attributed to five factors:

(1) Oxidation of sulphide minerals, ie. pyrite, marcasite.
(2) Mineral abrasion.
(3) Leaching.
(4) Carbonate equilibrium.
(5) Poorly drained soils containing abundant organic matter.

A liquid's pH is determined by its hydrogen ion concentration.

The role played by the hydrogen ion in chemical weathering cannot be over emphasized. This ion not only initiates disruption of crystal structures but its concentration also influences the solubility and precipitation of certain ions released during weathering.

Water is the ultimate source of hydrogen ions in the weathering environment. Oxidation of sulphide minerals, ie. pyrite or marcasite in the presence of water can result in solutions having pH values below 0, ie.

$2FeS_2 + 15/2O_2 + 4H_2O \quad Fe_2O_3 + 4SO_4 + 8H$

pyrite (Krauskoff, p. 112)

The high acidity experienced from this reaction results from the formation of very insoluble ferric oxide or hydrated ferric oxide $Fe_2O_3H_2O$, limonite. (Krauskoff, 1967)[33] Evidence of this process is present at outcrops which are heavily stained by yellow and brown ferric oxide.

Abrasion pH, as previously mentioned, results from hydrolysis of crushed mineral grains in water. Each mineral's abrasion pH is unique, ie. quartz's pH 6-7, feldspar's pH 8-9, calcite and dolomite pH 8-10, mica's pH 8-10.

As the degree of leaching increases, ions released during mineral weathering causing a characteristic alkaline pH will be removed. When the rate of removal of ions exceeds the rate of release from decomposing minerals, the pH may drop below neutrality causing acidic conditions. The duration, quantity and rate of infiltration of moisture received within a given weathering environment has a significant effect upon mineral weathering rates and water chemistry.

Hydrogen ions may also be created by the reaction of carbon dioxide to water yielding carbonic acid.

$CO_2 + H_2O = H_2CO_3$ (Krauskoff, 1967).

All natural waters which have been in contact with the atmoshere are dilute solutions of carbonic acid, 0.03M. (Carroll, 1970)[9]. Such solutions in equilibrium with the atmosphere at 25°C have a pH of 5.7, creating a stronger solvent than strictly neutral waters. (Krauskoff, 1967)[33]. If this water is in contact with other soluble material the pH will vary according to the presence of the other dissolved cations. Therefore "pure" water reacting with the atmosphere never possesses its theoretical pH value of 7.0 unless other dissolved material are found within the solution which neutralizes the effect of carbon dioxide.

Although carbon dioxide produces a weak acid its effects and significance are global. During chemical weathering carbonic acid aids silicate weathering and ion mobilities but its greatest role is controlling carbonate weathering and creating a buffering effect on acidic and basic solutions.

3.2.B.4 Influence of Redox Potentials, Eh, Upon Cation Mobilities

Some elements are capable of existing in more than one valance state, ie. iron, which can be native, ferrous or ferric, with respective oxidation states of 0, 2, 3.(Mason, 1966)[45] The stabilities of each oxidation state depends upon the energy involved in the addition or subtraction of electrons. This ability to bring about any oxidation or reduction process is a measure of energy which can be measured and is expressed as redox potential or Eh.

Eh varies with concentration of the reacting substances present. When H^+ or OH^- are involved Eh becomes pH dependent. Eh potential decreases as pH increases therefore oxidation of iron would proceed more readily in an alkaline environment.

The principal factors controlling redox potentials in natural weathering environments are (1) the accessibility of atmospheric oxygen and (2) the presence or absence of organic matter. (Loughnan, 1973)[42] Above the zone of saturation, oxidation (the gaining of electrons) tends to proceed; below this zone reducing conditions (the subtraction of electrons) are noted to prevail. Where organic matter is being oxidized to carbon dioxide a powerful reducing agent may exist above the zone of saturation. Eh is therefore partially controlled in nature by climate and topography. A hot well drained environment would favor oxidation whereas cool poorly drained areas favor reduction. Fig.3.6 illustrates the various positions of natural environments in relation to Eh and pH. The oxidation potential for the transition of ferrous iron to ferric iron falls within a range of values one would expect to encounter in natural environments, consequently both states are frequently found. A considerable difference in solubility exists between the two valance states of iron and its mobility is therefore greatly influenced by both Eh and pH. (Loughnan, 1969)[41] Fig. 3.6 clearly illustrates that the boundary between oxidizing and reducing environments separates most surface water from ground water.

When using Eh-pH diagrams for geological purposes, one must be aware of their limitations. Geological conditions impose a great deal more variables than expressed on most diagrams. The strongest oxidizing agent commonly found in nature is oxygen and the upper limit of redox potentials is $E^o = +1.23$ volts. Conditions higher than this decompose water therefore liberating O_2. Reducing agents are limited to substances which do not react with water. These reactions result in the liberation of hydrogen. The limiting redox potential is $e^o = 0.00$ volts. Local conditions may permit

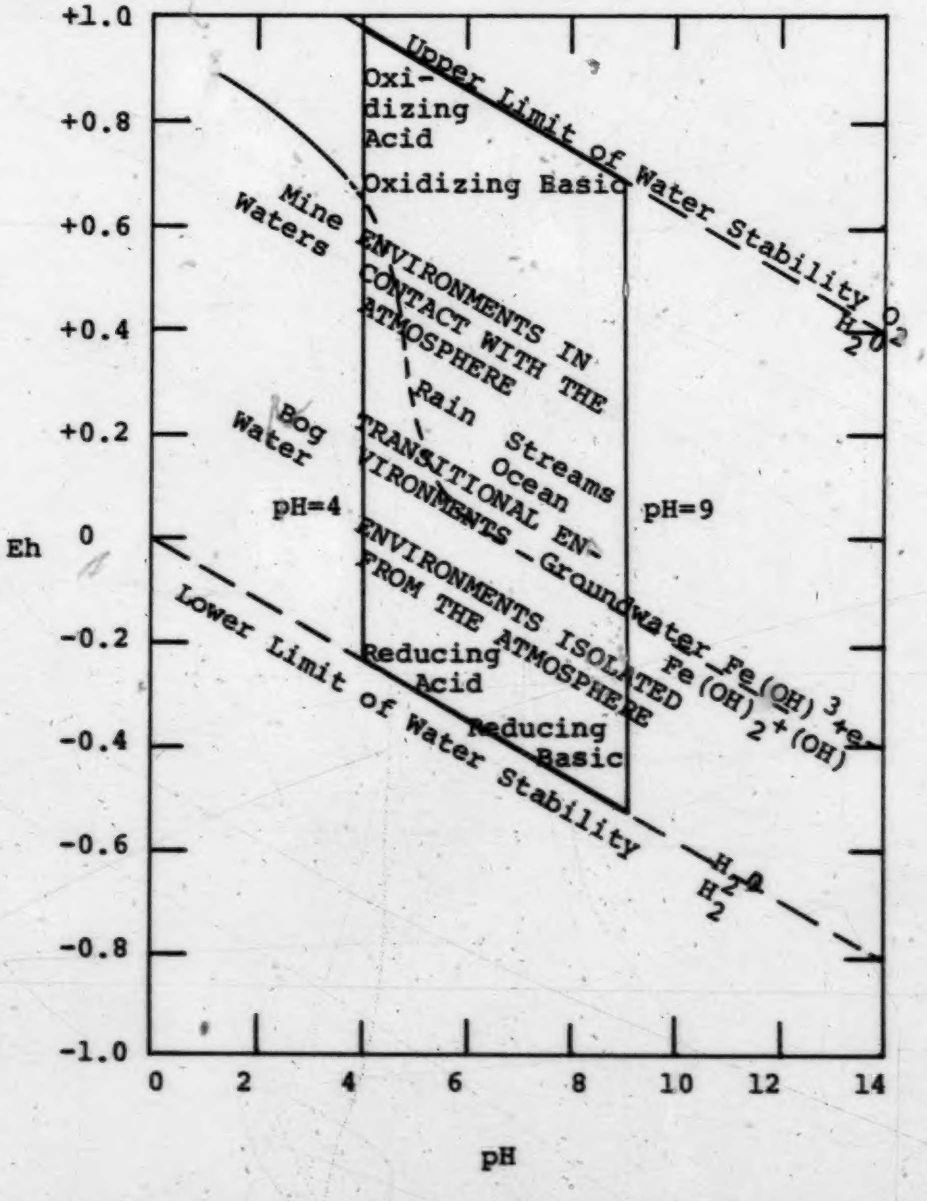


Fig.3.6 Approximate position of some natural environments as characterized by Eh and pH. Note, pH=9 forms an upper limit for most common basic environments while pH=4 sets the lower acidic limits for most environments. This graph shows conditions under which oxidation-reduction processes may occur in nature. Modified from Krauskopf, 1967, pg. 247 and Garrels and Christ, 1965, Loughnan pg. 42, 1978.

stronger reducing reactions. These may occur within bodies of organic material, ie. coal or petroleum, which are not in contact with water. (Krauskoff, 1967)[33]

In general only surface waters with good circulation are oxidizing. Confined waters quickly lose their oxygen content. Organic free water may lose their ability to oxidize by reacting with silicate minerals which contain ferrous iron or by contact with sulfides or ferrous carbonates. Chemical weathering reactions with silicates results in a rise in pH yielding reducing alkaline conditions. Environments containing organic matter quickly reduce the oxygen content of water thereby increasing CO_2 and H_2S content through biochemical reactions. "Below the water table level the environment can be assumed to be alkaline and reducing with the local exception of high rates of water flow." (Krauskoff, 1967)[33] Ground water which exhibits reducing characteristics quickly becomes oxidizing when exposed to the atmosphere. If they carry ferrous iron when oxygen is introduced the pH may become much more acidic, especially where there is a lack of bicarbonate (HCO_3^-). The iron will quickly precipitate out of solution as limonite. This reaction occurs as follows:

$$Fe^{2+} + 3H_2O = Fe(OH)_3 + 3H^- + e^-$$

(W. C. Krumbein and R. M. Garrels)[34]

This reaction is very common within the Grassy Mountain area.

3.2.B.5 Influence of Ionic Potential Upon Cation Mobility

Ions in solution attract water molecules. The number of water molecules which can be packed around an ion depends upon its size and the intensity of charge on its surface. Therefore two ions possessing similar charges but of different size would behave differently in water. An ion's ability to be hydrated is proportional to its charge in valancy units (Z), and inversely proportional to its ionic radius in Angstroms (r). This Z/r factor is known as ionic potential.

Cartledge (1928)[10] and Goldschmidt (1937)[23] were the first to realize the importance of ionic potential and its relation to an ion's behavior and mobility in water. Ions can be arranged into 3 groups; Fig. 3.7. Those with low ionic potentials (Z/r 3.0) tend to pass into true solution during the weathering process. Ions with intermediate ionic potentials (Z/r 3-9.5) quickly precipitate out of solution by hydrolysis and concentrate as residues. Finally, upon weathering, ions whose Z/r ratios exceed 9.5 form soluble anionic radicals. In general Z/r ratios provide a useful guide to the behavior of various ions when weathered. This factor is not independent, as Eh and pH may exert equally important influences controlling ions' mobilities. For example, iron in the ferrous state is stable in solution with an ionic potential of 2.7. When oxidation occurs, iron's ionic potential alters to a much higher state, 4.7, resulting in its precipitation.

3.2.B.6 Oxidation

Oxidation is the most visible chemical weathering process. Iron oxides are the most conspicuous and common products of oxidation. The color of simple iron oxide is red, while that of iron hydroxide ranges from yellow to brown. Elements which are commonly oxidized are iron, manganese,

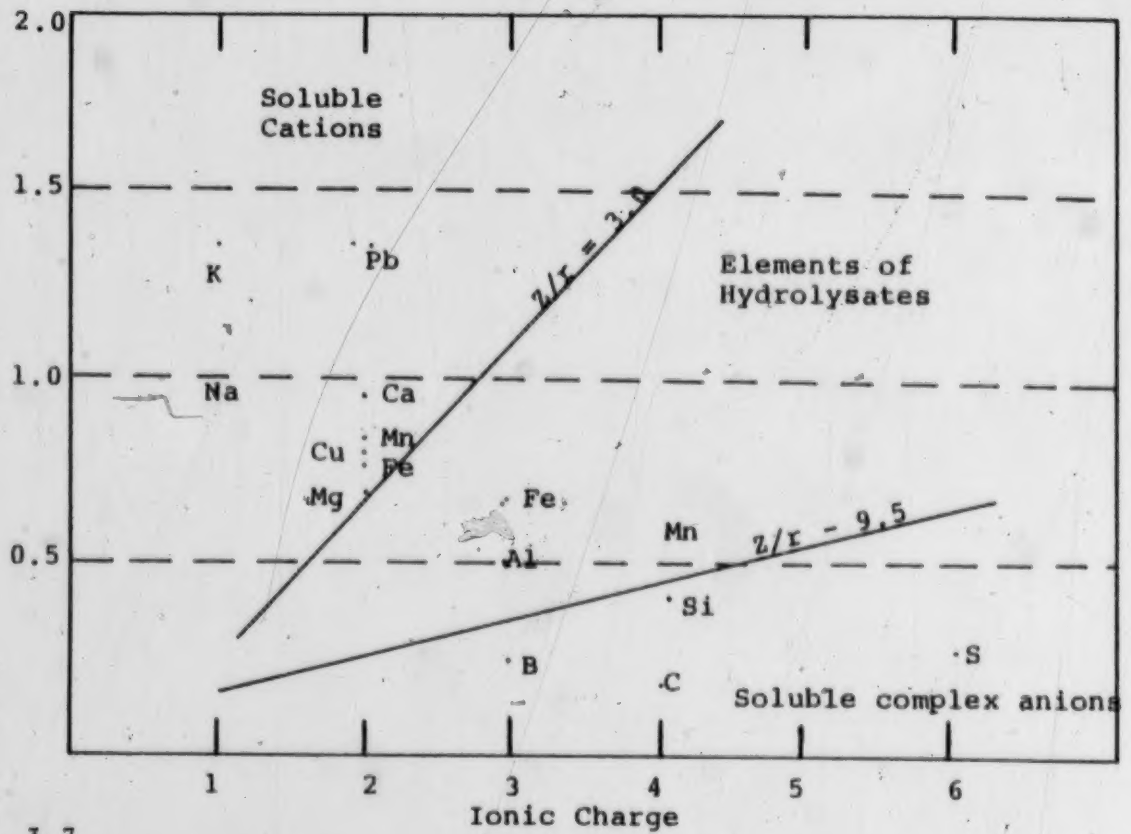


Fig. 3.7
Ionic Potentials of Specific Elements. Three broad categories exist, (a) those with low ionic potentials, Z/r 3.0, passing into true ionic solution, (b) those of intermediate ionic potential, Z/r 3.0-9.5, which quickly precipitate and (c) elements of high ionic potential, Z/r 9.5 forming soluble anionic radicals upon weathering. Source modified from Mason, 1966, p. 167; Loughnam, 1973, p. 51.

sulphur and carbon. Metals which form very insoluble oxides or hydroxides, ie. iron, lead to precipitation of the solid. The resulting acidic solutions can be very strong, ie. pyrite oxidation, which forms menatite, limonite, and sulphuric acid. In arid regions oxidation of pyrite commonly yields iron sulphate minerals as well as limonite and hematite.

In humid areas practically all the iron is oxidized and precipitated as hydrated oxide or limonite. (Krauskoff, 1967)[33]

Organic carbon may be oxidized through the action of microorganisms acting as catalysts. This oxidation process can be significant as carbon dioxide liberated may take part in altering the solution's pH and in the hydrolysis reaction, (Brounlow, A.H., 1979)[5]

Cation mobilities may therefore be influenced by oxidation which results in numerous reactions involving the release of several elements. Sulphur, manganese, iron and carbon are frequently found together in clastic sediments such as those at Grassy Mountain. The simultaneous oxidation of these minerals may create a complex water chemistry from waters which pass through their parent material.

3.2.B.7 Fixation of Common Cations

The phenomenon of cation fixation is apparent in many weathering reactions. Potassium, in contrast to most cations, possesses a strong tendency to be retained and is useful to demonstrate fixation. The average igneous rock contains almost equal amounts of potassium and sodium, however in sedimentary rocks there is a significant dominance of potassium over sodium.

(Clark, 1924; Mason, 1966[45]) Sea water, nature's sump for soluble products of weathering has a sodium potassium ratio of 10:1. The reason for such differences in concentrations of sodium and potassium from primary rocks is that unlike sodium, potassium released during weathering often becomes trapped within secondary clay minerals. Potassium's preferential entrapment results from its unique size which is almost identical to the oxygen molecule occupying interlayer positions within clays. Scientists (Wear and White, 1951[68]; Loughnan, 1969[41]; Mackenzie, 1963) discovered that ions with a radius of 0.85 Å or less were significantly fixed by montmorillonite if they were subjected to alternating wetting and drying cycles.

3.2.B.8 Role of Leaching Upon Chemical Weathering

The most important single factor in controlling the rate of parent material breakdown and the production of secondary minerals is the quantity of water percolating through the weathering environment. (Bergman, 1976[2]; Pedro, 1961[53]; Carroll, 1970[9]; Birkeland, 1974[3]; and Loughnan, 1969[41]). Jenny (1951)[29] summarizes the importance of percolating water by writing, "The most active agent in soil profile development is water. As long as water passes through the solum, substances are dissolved, translocated, precipitated and flocculated and the soil is not in a state of rest."

Rainwater percolating through the weathering environment tends to remove soluble ions released by hydrolysis at a mineral's surface. This permits fresh exchange sites to be established and total weathering to occur. Given sufficient precipitation, time, and a permeable medium even the most stable parent minerals, ie. quartz can be destroyed without an erosion or geological process.

The factors previously mentioned influence the mobilities of ions in water. Other factors exist which play a significant role in controlling ion mobilities. The most important of these are carbonate equilibria and groundwater chemistry.

3.2.B.9 Carbonate Equilibrium

The solubility of calcium carbonate ($CaCO_3$) is determined by the pH of its environment which controls the relationship between carbonic acid and the carbonate mineral. Three carbonate species are present and they exist in solution as carbonic acid (H_2CO_3), bicarbonate ions HCO_3^- or carbonate ions $CO_3^{=}$. Fig. 3.8 illustrates which carbonate species is dominant within a particular pH environment. HCO_3^- exists within the pH range of most natural waters and therefore it is the most common carbonate species found.

Factors which influence the solubility of $CaCO_3$ are:

(1) Temperature - CO_2 is less soluble in warm waters. Therefore warm waters contain less carbonic acid and have a lower $CaCO_3$ solubility.

(2) Pressure - increase pressure results in more CO_2 dissolving into water thereby increasing $CaCO_3$ solubility.

(3) Decay of organic matter - in soils this results in increased available CO_2 thereby increasing $CaCO_3$ solubility.

(4) Organic activity - in water, plants utilize CO_2 present thereby decreasing its presence and $CaCO_3$ solubility.

(5) Organism in soils - increase available CO_2 thereby

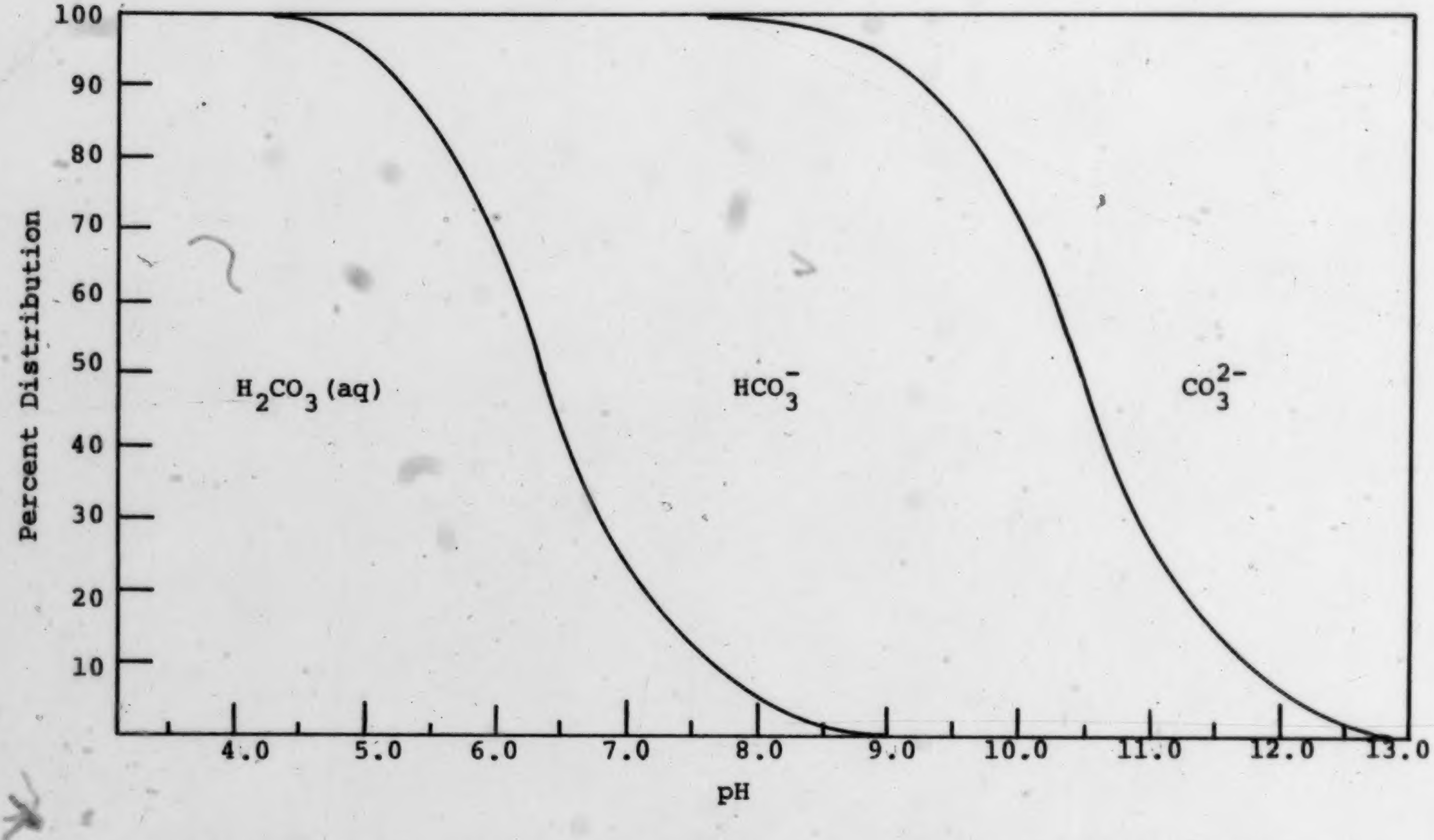


Fig. 3.8 Percentages of carbonate species in solution as a function of pH. Temperature = 25 C. Pressure 1 atm. All CO_2 molecules in the liquid are assumed to be combined with H_2O. Source, Brownlow, 1979, p. 172.

increasing $CaCO_3$ solubility.

(6) Acidity of the environment.

The most significant characteristic of the carbonate system towards chemical weathering are its buffering effects. A buffer by definition (Krauskoff) is "a solution capable of absorbing considerable H^+ or OH^- without much variation in its pH." If an acid was produced during weathering and added to a solution containing HCO_3^- or $CO_3^=$ and in the presence of calcite, the following buffering reactions would occur:

$HCO_3^- + H^+ \quad H_2CO_3^-$ (eq. 11) Krauskoff (1967)

$CaCO_3 + H_2CO_3 \quad 2HCO_3^- + Ca^{++}$ (eq. 12) Krauskoff (1967)

This solution would cause $CaCO_3$ to become more soluble therefore, more calcite would dissolve.

However, if a base was present in a carbonate solution, the following would occur:

$OH^- + HCO_3^- \quad CO_3^= + H_2O$ (eq. 13) Krauskoff (1967)

$OH^- + H_2CO_3 \quad HCO_3^- + H_2$ (eq. 14) Krauskoff (1967)

$Ca^{++} + HCO_3^- + OH^- \quad CaCO_3 + H_2O$ (eq. 15) Krauskoff (1967)

Carbonate minerals' solubility is controlled naturally by the presence of carbonate ions; H_2CO_3, HCO_3^-, and water. The buffering effect of the carbonate system has resulted in most natural water's pH to maintain a (Mason, 1966)[45] range of 4-9, thereby restricting and promoting various degrees of chemical mineral weathering and ion mobilities.

3.2.B.10 Groundwater Chemistry

The chemistry of groundwater is commonly different from that of surface waters within the same area. Mobilities and solubilities of ions within solution commonly change dramatically at surface water-groundwater interfaces.

Schwartz (1974)[65] found that groundwater chemistry generally acquires its characteristics from the physical transport of material through a porous media accompanied by many complex chemical and biological processes. The chemical composition of most natural groundwater systems are products of chemical processes such as dissolution of porous medium, precipitation of mineral phases, ion exchange between pore fluids and the porous medium, and osmosis or reverse osmosis reactions. Biological activity may control chemistry by addition or removal of CO_2 and by the reduction of sulpahate ions.

The relative abundance of dissolved constituents within groundwater largely depends upon the dissociation kenetics of the porous medium. Mineral dissolution within ground water are controlled by the same factors as surface water, ie. pH, temperature, parent material and Eh. Schwartz and Domenico (1973)[66] concluded that within natural groundwater systems it is difficult, sometimes impossible, to differentiate between processes causing specific water chemistries due to the multiplicity of chemical and biological interactions. Their research revealed important facts:

(1) Mineral dissolution is the most important mass generating process with the system. Any decrease in the concentration of major cations or anions indicates that the dissolution process is being modified by one or more other processes.

(2) Saturation constraints are important in the chemical evolution of groundwater. Relatively large changes in the specific saturation levels for calcite and dolomite resulted in relatively small variations in the simulated concentration of Ca^{++}, H^{+}, and HCO_3^- at the dolomite equilibrium point.

(3) The partial pressure of CO_2 gas in soil zones of water recharge areas is most effective in controlling groundwater composition. Any process initially lowering groundwater pH will ultimately produce higher concentrations of Ca^{++}, Mg^{++} and HCO_3^- in solution.

(4) Equilibrium with respect to a mineral phase does not imply that the concentration of the ionic species related to the equilibrium remains unchanged. The effect of adding common ions from other dissolution or process is to shift equilibrium concentrations.

(5) The direction of groundwater flow determines the order in which the spatially distributed processes occur. Changes in chemical composition along a flow path depends in part on the duration of the processes acting in relation to the residence time of the flow.

CHAPTER 4

FIELD RESEARCH AND OBSERVATIONS

Field research was conducted during the summer season of 1978 and 1979. Time was initially spent selecting the most ideal locations at Grassy Mountain which would reveal natural processes and by-products of rock weathering. From these locations samples of fresh rock, weathered rock and water were collected for laboratory studies and observations. Any visible signs of natural chemical and/or physical weathering processes and products were noted at the time of collection.

Samples and locations selected at Grassy Mountain to represent and observe "natural" weathering processes and products are discussed in this section. All photographs referred to in this section are found in Appendix 6.

4.1 Highwall Section

Reasons for choosing the highwall for this research are:

(1) The approximate duration of weathering which the highwall has experienced is known, ie. 29 years.

(2) Overburden extracted during mining resulting in the highwall formation is located in close proximity to the site.

(3) The variety of lithologies present in the section allow scope for good comparative weathering studies.

(4) Relative ease of access to and on the highwall.

(5) Unweathered rock samples can be obtained.

The highwall section is located on the west side of the V-shaped open pit trench approximately 500 metres north of the "twin ponds" (Map 2, Photos 1 and 2). The highwall is approximately 24 metres high and consists of lithologies from the Mutz Member of the Kootenay Formation. The detailed description of the highwall made during the study is reported in Appendix 2. Figure 4.1 illustrates the highwall's geology. Samples of fresh and weathered rock representing each major lithologic unit within the highwall were collected for description, laboratory analysis and experimentation (Appendix 2).

The highwall was examined to determine each lithology's resistance to physical and chemical weathering. Photographs of each lithologic unit were taken to record surface alterations induced by rock and mineral weathering, ie. surface precipitates, fracture density, weathered rock fragment size and shape, depth of weathering,.and color changes.

Loose samples of weathered lithologies from the highwall were collected at its base to determine rock fragment size, weathered lithologic frequency of occurrence. Determining the relative percentage of each lithology which has fallen from the highwall and comparing this percentage with the occurrence of each lithology within the section could help to establish each lithology's resistance to weathering.

4.2 Springs

Water from springs emerging at the base of overburden spoil or rock outcrops carry various concentrations of specific ions such as Ca^{++}, Mg^{++} Na^{+}, K, $SO_4^{=}$, HCO_3^{-}, $CO_3^{=}$, Fe, Al, Cu, Zn, S. These ions indicate weathering processes occurring within the material travelled through. Spring water emerging

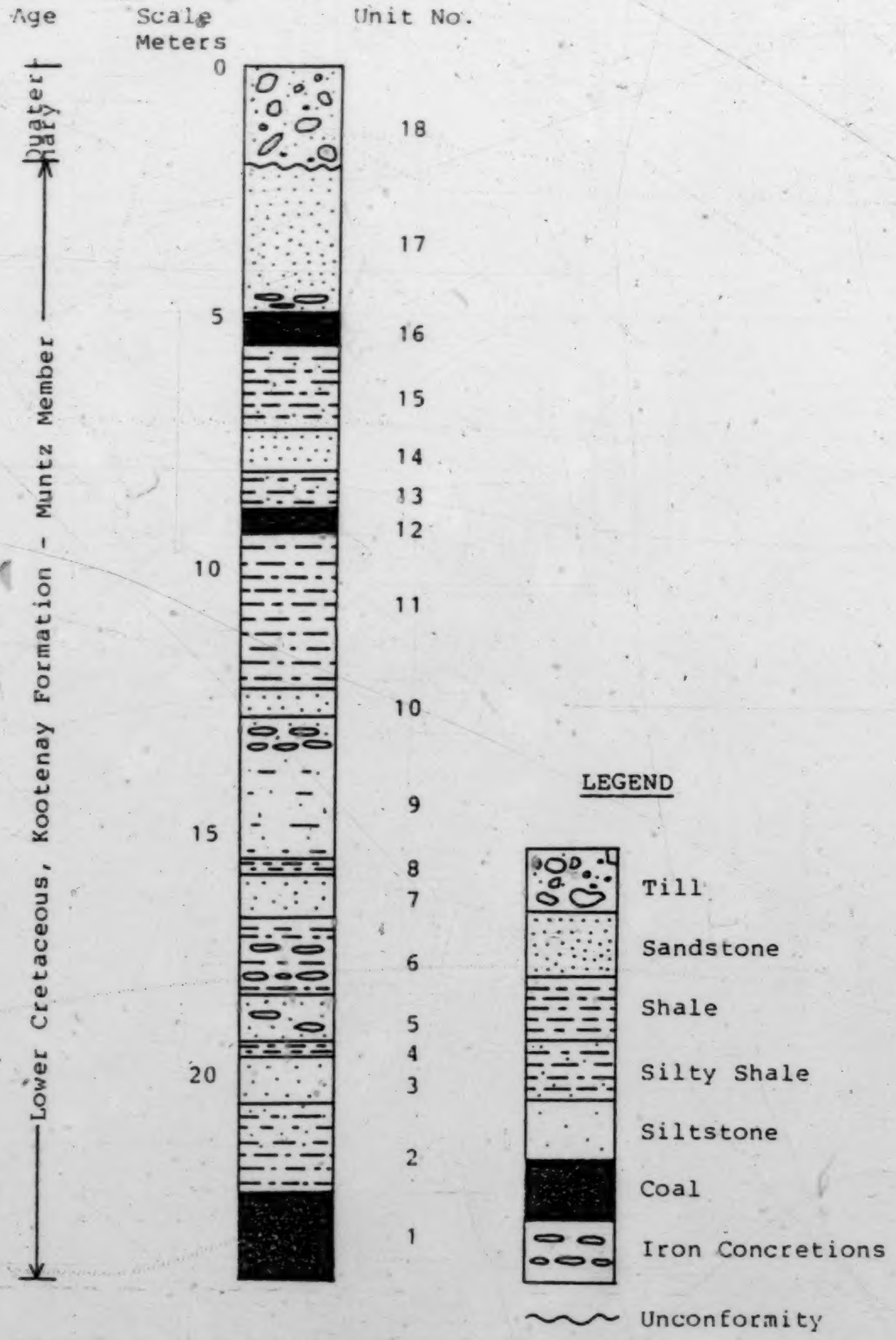

Age
Scale Meters
Unit No.
0
5
10
15
20
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Quaternary
Lower Cretaceous, Kootenay Formation - Muntz Member
LEGEND
Till
Sandstone
Shale
Silty Shale
Siltstone
Coal
Iron Concretions
Unconformity

Fig. 4.1 Grassy Mountain Highwall Geologic Section

from overburden approximately 100 metres south of the highwall section and within the open pit trench was collected and analysed at one-month intervals from May-October of 1977 and 1978 by the Geological Survey of Canada (Photo 3). Water temperature of the springs remained relatively consistent, fluctuating between 13°C in August and 6°C in October. Water flow was not measured but a noticeable decrease in flow occurred from June through to October.

4.3 Twin Ponds

Water in the Twin Ponds at Grassy Mountain occupy the site of former open pit mines. These ponds are suspected to be sumps for water draining through overburden and therefore would contain dissolved minerals and ions which may indicate weathering processes occurring within the overburden.

4.4 Overburden Spoil

An area 7.5 M square located upon a relatively level surface of an overburden pile 100 metres N.N.E. of the highwall section was selected for weathered rock sampling and weathering observations. The following factors supported this choice.

(1) The overburden consists of cast rock from the open pit trench at the sampled highwall section, therefore comparison of results between fresh and weathered rock samples could be made.

(2) The overburden has remained undisturbed for approximately 28-29 years, therefore rates of natural rock weathering

may be determined.

(3) Spring waters carrying dissolved ions emerged from these overburden piles.

Level areas at overburden's surface commonly displayed a pebble, "boulder pavement", which may be indicative of wind erosion (Root 1976). Several sandstone and/or siltstone boulders in excess of 10 cm were present in the surface (Photo 4). Vegetation consists of a few grass patches on the lee side of the boulders or the site of weathered shale boulders.

Samples representing the upper 0-2 cm, 2-10 cm and 0-100 cm depths of overburden were collected for grain size, lithology, specific gravity, weathering analyses and for use as a control to represent naturally weathered overburden. Photographs of the overburden's surface and several individual boulders were taken to record weathering processes and products.

CHAPTER 5

FIELD AND LABORATORY PREPARATION

5.1 Sample collection and Preparation

Sample analysis were undertaken with the following objectives in mind:

(1) To reveal natural weathering processes and products occurring at Grassy Mountain.

(2) To obtain fresh rock samples for analyses and experimental laboratory weathering processes employed in this research.

(3) To reveal the relative proportions of each lithologic unit present.

(4) To obtain data which can be used to compare and relate artificial and natural weathering.

Fresh rock samples were collected at the highwall by chipping away the weathered surface or portion of each exposed lithologic unit. A sample of each unit was dug out or chipped off, placed in a plastic bag, which was then sealed and returned to the University of Alberta for further experimental analysis.

Weathered rock samples were collected at the highwall's base and from the overburden pile. Samples at the highwall base were collected in wooden boxes measuring 50 cm x 30 cm x 20 cm high which were placed for a period of one month at four locations along the base of the highwall. Weathered rock fragments falling off the highwall were trapped in these boxes. The relative percentage of each lithology within the boxes was determined and compared to the relative percentage of each similar lithology occurring within the highwall. This comparison revealed each lithology's resistance to weathering. These samples were not used to study weathering as they would only represent recent products of weathering.

Rock samples from the overburden spoil location were used to study natural rock weathering. A level area on the spoil pile was chosen for sampling. String was used to mark off a square-shaped area measuring 7.5M on each side. The area was further divided into nine smaller 2.5M squares measuring 2.5M on each side. At the intersection of each square samples of weathered overburden were collected from a depth of 2-10 cm by scraping away the upper 0-2 cm portion of windblown material and excavating with a metal spoon an area approximately 10 cm x 10 cm to a depth of 10 cm. Sixteen of the 2-10 cm depth samples were collected. One sample representing the upper windblown 0-2 cm portion of the overburden was taken from an area 60 cm x 60 cm. These samples were placed in plastic bags which were sealed and taken to the laboratory for grain size, lithologic, weathering and specific gravity determinations. These samples would also provide a control for comparing natural rock weathering to artificial rock weathering.

Two bulk samples representing overburden 0-100 cm deep were also collected from overburden area. These samples were retained for grain size and lithologic analyses. While excavating these samples it was observed that shale boulders at depths greater than 50 cm revealed signs of minor weathering compared to highly weathered shale boulders at the surface. Materials at depths greater than 50 cm were moist and cool (12°C) compared to the surface material which was dry and warm (40°C on the overburden surface during bulk sample excavation), illustrating a major weathering environment change prevails at shallow depths. Individual rock samples exhibiting distinct responses to weathering were also collected from the various locations at Grassy Mountain.

Water samples were collected by the G.S.C. at the springs and twin ponds previously described. Each sample was filtered and placed in plastic containers which were sealed and returned for chemical analyses to Environment Canada's laboratories in Calgary. At the time of collection the water's temperature and pH was measured and recorded.

All visible signs of rock weathering such as surface precipitates, fracturing, staining, discoloration, rock disintegration, and depth of weathering on the highwall or overburden piles were photographed using an Olympus OM1. These photographs were useful in comparing lithologies' response to weathering.

5.2 Laboratory Procedures

5.2.A Sample Preparation

The three groups of rock samples collected during the field season were composed of similar lithologies subjected to different degrees of weathering. These groups consisted of:

(1) Fresh rock samples obtained from the highwall section at Grassy Mountain.

(2) Naturally weathered overburden taken from the open pit adjacent to the highwall section 29 years ago.

(3) Individual rock samples illustrating various stages of natural weathering.

5.2.B Crushing

It was necessary to break down the fresh rock samples to finer sizes in order to observe the effects of particle size upon artificial weathering. "Fresh" rock samples were crushed using a mortar and pestle and then sieved.

5.2.C Sieving

Two rock groups were sieved, naturally weathered overburden and crushed fresh rock samples. The seventeen overburden samples were oven dried over a 24-hour period. Each sample was shaken through a nest of sieves separting the material into the following particle sizes; pebble, granule, very coarse-coarse sand, medium-very fine sand, coarse-medium silt, and fine silt-clay. The sample retained in each size fraction was weighed to determine its relative proportion of the total sample. Crushed fresh rock samples representing each individual lithologic unit within the highwall were separately sieved into the following particle sizes:

(1) Pebble to very coarse sand (1-4mm)*

(2) Very coarse to fine sand (1-1/16mm)*

(3) Silt-clay sizes (1/16mm)* *Wentworth

These samples would be used later in an artificial weathering experiment. All sieved samples were retained in plastic bags.

5.2.D Preparation of Crushed Fresh Rock for Artificial Weathering

Two groups of samples derived from crushing and sieving fresh rocks were prepared for artificial weathering.

The first group was prepared to study the effect of grain size upon artifically induced chemical weathering. The three grain size groups used were those separated during sieving. The crushed fresh rock was mixed in proportions equalling that which would be found within the overburden spoil piles. These proportions were controlled by the relative percentage of each lithology within the highwall section and determined the following blends of crushed lithologies for each of the three grain size categories.

Table 5:2

Lithology	# of units represented	% by weight of total
Sandstone	5 units	34.7%
Siltstone	6 units	26.6%
Silty Shale	2 units	16.8%
Shale	1 unit	12.6%
Coal	2 units	9.3%

*See Appendix #5 for exact proportion each unit contributed.

The second group was prepared to examine the effects of artificial chemical weathering of specific lithologies. Four lithologic mixtures, all within the sand size range (1-1/16mm), were prepared by blending similar units according to their relative proportion within the highwall. These sample mixtures consisted of sandstone, siltstone, shale and coal.

5.2.E Grain Size and Lithology Correlations

The seventeen sieved overburden samples were examined under petrographic and binocular microscopes in order to determine the quantity of specific lithologies in each size range. This was done by point counts (50 per slide) on a calibrated microscope stage. Lithological investigation provided information concerning weathering properties of each unit at Grassy Mountain. Comparing percentages of each lithology present in each size fraction with percentages of each lithology present within the highwall section described, provides information relating to the east of physical breakdown experienced by each lithologic group.

5.2.F Specific Gravity

Specific Gravity for the weathered overburden samples was determined for particle sizes less than #10 mesh. The method employed is outlined in pages 104-110 in the Lab Manual for Soil Mechanics (Raymond F. Dawson, 1959). Results were tabulated and averages calculated. These data would aid in an approximate lithological analysis of the finer-sized fractions within weathered overburden.

5.2.G Non-Polarizing Binocular Microscope

The binocular miscoscope was used in examining and describing all field samples as well as whole and thin section samples representing fresh and artifically weathered specimens. This method along with field descriptions and thin section analysis enabled a detailed lithologic highwall section to be produced.

5.2.H Thin Sections

A list of thin sections prepared by lab technicians at the University of Alberta is reported in Appendix 7. Comparison of several factors during thin section descriptions revealed differences and relationships between weathered and fresh samples. These relationships helped determine the degree of accelerated rates of weathing produced experimentally. Factors considered most important in establishing this relationship were:

(1) Mineral alteration; type, extent, and position of alteration.

(2) Weather rind thickness. (Birkeland, Winkler, Keller, Carroll, Ollier)

(3) Precipitate thickness and type on rock fragments' surface and within matrix.

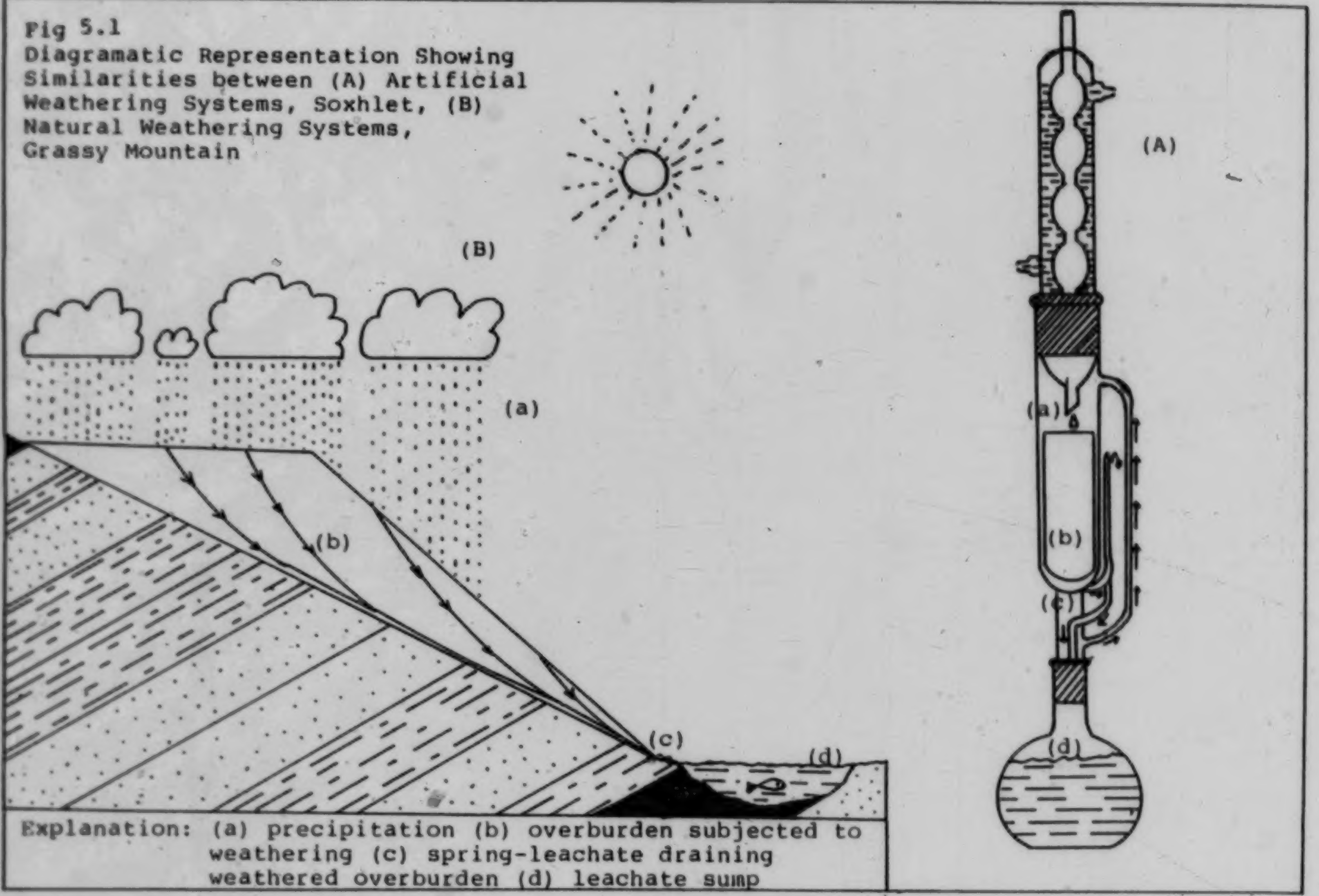
(4) Degree of fracturing caused by weathering.

(5) Color and lustre alterations of similar mineral grains in fresh and weathered samples.

(6) Lithologies present within specific size fraction.

Rocks subjected to similar conditions of weathering can have their rind thickness measured, plotted and a rough estimate of duration of weathering determined. Thicknesses were determined by using the calibrated scale and knowing the diameter of the field of view for each lens used. Graphical plots representing weather rind thicknesses from naturally

Fig 5.1
Diagramatic Representation Showing Similarities between (A) Artificial Weathering Systems, Soxhlet, (B) Natural Weathering Systems, Grassy Mountain



Explanation: (a) precipitation (b) overburden subjected to weathering (c) spring-leachate draining weathered overburden (d) leachate sump weathered overburden and artifically weathered rocks were constructed. Comparisons of rind thickness from these two sources may provide information regarding the rate of accelerated artificial weathering.

Lustre and color of samples were observed using reflected light. For some samples, ie. coal, this was the only visible sign of weathering. These weathering features were purely objective and could not be used to correlate natural-artificial weathering rates.

5.2.I Producing an Artificial Weathering Environment

An experimental procedure which would most closely represent the weathering cycle and processes within overburden piles at Grassy Mountain was developed using a soxhlet extraction apparatus. A combination of water and temperature is responsible for most natural weathering processes. (Birkeland 1974, Carroll, Ollier, Winkler, Kerr) The soxhlet apparatus creates an environment with elevated temperature and increased moisture resulting in accelerated rock weathering (Pedro, 1960)[53]

The soxhlet extractor operates in a cyclical pattern constantly leaching samples by recycling water. This process closely resembles natural geochemical weathering processes at Grassy Mountain (Fig. 5.1). Two distinct geochemical phases exist within the soxhlet apparatus; (1) the residual phase (eluviate) containing elements which remain in situ after leaching of primary minerals and are combined to form new minerals (b in Fig. 5.1) and (2) the leached phase (lesivate) which comprises all the elements likely to be washed away after being leached by weathering (c and d in Fig. 5.1).

At Grassy Mountain the eluviate is represented by overburden piles and the lesivate corresponds to springs and ponds formed from water which has percolated through the weathering overburden material.

Six glass soxhlet extractors consisting of three distinct segments, the flask, condenser and extractor were used. Each segment represents specific zones within nature (Fig. 5.1). The hollow tube of the condenser is open to the atmosphere during artificial weathering and therefore acts as nature's clouds and atmosphere. Water droplets falling from the condenser into the extractor and onto the rock sample, initiate weathering. In the extractor segment there are two distinct zones:

(1) An upper zone which is constantly moist without being inundated so that reactions occur in contact with air representing the atmosphere zone.

(2) Lower zone where rock fragments are temporarily submerged in water. Here "weathering" takes place between a state of total immersion and superficial wetting.

Humidity and temperature of the "rainfall" within the extractor are higher than experienced at Grassy Mountain. Because of this, gasses dissolved within the percolating waters will differ from normal rain. Soxhlet "rain" contains only half as much dissolved oxygen and one-quarter as much carbon dioxide as natural rainfall (Pedro 1960). At this temperature, 63°C, the neutral point of distilled water is at pH 6.5. Weathering within the extractor unit represents a physical environment similar to a hot, moist tropical climate with abundant rainfall. The water level within the extractor rises until 90% of the sample becomes submerged. At this point water containing leached products of artificial weathering is automatically siphoned off, falling into the erlymyer flask below. The leachate is boiled and the cycle repeats itself.

The following conditions and sequence of events responsible for artificial weathering are:

(1) Double distilled water is placed in a flask and allowed to boil.

(2) Steam rises, reacts with atmospheric gasses, condenses and falls as 63^{o}-65^{o}C water droplets onto rock samples below.

(3) Rainfall is constant at a rate of 1450mm/day.

(4) Water level within the extractor rises until approximately 90% of the rock sample is submerged.

(5) Siphoning occurs draining the leachate from the extractor into the flask below.

(6) Leachates are siphoned approximately every 107 minutes or 13.5 times per day.

(7) The duration of artificial weathering is chosen and controlled. At specific intervals of time the process is interrupted in order to collect leachates and replenish the system with fresh distilled water.

Weathering systems and components at Grassy Mountain and within the soxhlet apparatus are similar. Intensity, duration and concentration of these components differs resulting in different rates of weathering occurring between the two systems. Knowing the difference between the two weathering system's components will enable a calculation of the degree of accelerated weathering within an artificial system over natural weathering.

5.2.J Methods of Artificial Weathering

Samples prepared for artificial weathering represented various grain sizes and lithologies.

Different grain sizes from the same lithologic mixtures were first to be artificially weathered. Both gravel and sand sized mixtures had six samples each weighing 60 grams placed in cellulose thimbles and set in the extraction unit. Only two silt-clay sized samples, each weighing 40 grams were placed in cellulose thimbles within the extraction unit. Each size range had an extra sample prepared and retained for control purposes. Each gravel sized sample used 300 ml of double distilled water which was placed in a 500 ml erlymyer flask. The initial temperature and pH of the water was recorded. Each sand and silt-clay sized mixture used 400 ml of double distilled water. The water was boiled to initiate artificial weathering. Artificial weathering continued for a period of seven days at which time each leachate was removed from the flask, its volume and pH determined and then stored in an airtight plastic bottle. The flasks were cleaned and then refilled with the same amount of double distilled water used at the beginning of artificial weathering. Replacement of the leachate with new double distilled water occurred every seven days for a three-week period with the exception of silt-clay sized mixtures which were weathered for four one-week periods. Leachates for each sample group and each period of weathering were then prepared for chemical analysis by an atomic absorption apparatus.

The second series of weathering involved sand sized samples of various lithologies. Artificial weathering procedures duplicated those run during grain size experimentation but sample mass and duration of weathering was altered. Fifty gram samples were "weathered" over a four-week period. Four hundred ml of double distilled water was replenished at one-week intervals and the leachate stored in plastic containers to be analysed at the termination of this stage of experimental weathering.

The degree of contamination from the soxhlet apparatus was determined by proceeding with artificial weathering in the absence of rock samples. Four hundred ml of double distilled water was placed within four flasks and allowed to boil. Two extractors contained cellulose thimbles while two units functioned with only their basic glass components. The pH of each flask's water was determined prior to boiling and upon the completion of the experiment seven days later. At this time the leachate volumes were recorded and solutions stored in airtight plastic bottles for later chemical analyses by atomic absorption.

The process and temperatures of artificial weathering for each set of samples were similar. Only sample mass, water volume and duration of weathering were altered.

Upon completion of the artificial weathering a representative mixture of each grain size and lithology was retained. This sample will be used for comparative studies of fresh versus artificial and naturally weathered samples. From each representative sample, one thin section is produced and the remainder of the sample is examined with the binocular microscope.

All leachates from each period of artificial weathering were analysed to determine concentrations of Ca^{++}, Mg^{++}, K^{+}, Na^{+}, Fe, Zn, Cu, Ni, Pb, Al, SO_4, HCO_3^-, $CO_3^=$ and total alkalinity.

5.2.K Leachate Preparation for Atomic Absorption Analyses

Leachates prepared for atomic absorption analyses are often involved in either a process of dilution or concentration. Only magnesium concentrations were determined from the original leachate collected at the end of each weathering period. Altering the original leachates concentration is necessary because of the various sensitivities of the atomic absorption unit towards each element analysed. Calcium, potassium, sodium and silicon required dilution of 5 to 20 times as their concentration was high and the atomic absorption unit sensitive to low concentrations. Leachates obtained from the initial stages of weathering required the greatest dilution. Concentrating leachates by a factor of 20 was achieved by evaporating 200 ml of leachate in teflon beakers to a volume of 10 ml. This strength was often required in order to detect any elements from third and fourth week leachates. Concentrated leachates were used to analyse solutions for iron, aluminum, copper, zinc, nickel and lead. Hydrochloric acid was added to each concentrated leachate to create an acidic solution in order to mobilize metal ions (Fe, Al, Zn, Pb, Cu, Ni). It is essential that the volume of leachate analysed in mls. be twice that of the number of elements sought by the atomic absorption unit.

Carbonate, bicarbonate, alkalinity and sulphate concentration were determined on normal leachate solution by R. M. Hardy and Associates (United Petro Laboratories Ltd.) using titration and gravimetric techniques described in Environment Canada's Analytic Method Manual (1978).

5.2.L Atomic Absorption Analysis

An atomic absorption spectrophotometer facilitated the determination or iron, aluminum, copper, zinc, lead, manganese, nickel, calcium, magnesium, sodium, potassium and silica contents.

Analytical procedures followed during atomic absorption analyses are outlined by Butler (1971)[8] and the prescribed Perkin-Elmer atomic absorption manual. Each element sought uses a minimum of three known standards as controls. Graphical plots and digital readouts for each standard were determined and recorded. The element's concentration within each leachate was then determined at least twice to ensure that graphical plots and digital readings were reproducible within acceptable prescribed limits. Upon completion of the leachate analyses all standards were re-examined to ensure their concentrations fell within acceptable reproducible limits. Once acceptable results had been obtained, concentration graphs from control solutions were drawn, leachate values plotted on these graphs and their unknown concentration determined. This method was consistently conducted for analyses of each element.

CHAPTER 6

FIELD AND LABORATORY RESULTS

6.1 Visible Evidence of Physical and Chemical Rock Weathering at Grassy Mountain

All photographs referred to in this section exhibiting weathering observed at Grassy Mountain are in Appendix 6. According to Peltier and Ollier, the environment at Grassy Mountain results in weak to moderate physical and chemical rock weathering with strong to weak intensities of frost shattering (Fig. 3.1). For this reason visible examples of rock weathering in nature often result from both chemical and physical weathering.

Each lithology weathers according to its internal structure and composition.

Finely laminated lithologies such as shale and/or silty shale or units containing interbedded layers consisting of fine laminations, fossil fragments, fractures and platy clay minerals are very susceptible to physical-chemical deterioration (Rapson, 1965) (Photos 4, 5, 6). Planes of weakness allow penetration of water which under conditions of freeze-thaw, wetting-drying or mineral absorption may quickly shatter the rock into flaky, platy chip-shaped fragments often less than 1 cm in size. Weathered surface of these lithologies often exhibit iron staining or surface precipitates such as calcium sulphate. These precipitates may coat the entire rock surface after only a few years' exposure to weathering (Photos 7, 8).

Massive lithologic units such as sandstone and siltstone are very resistant to both chemical and physical weathering and commonly form ledges at the highwall section or boulders at the surface of weathered overburden piles (Photos 9, 10). Weathering of these lithologies takes place along bedding planes or interbeds of finely laminated material (Photo 11). Oxidation of ferrous iron is common at the weathered surface of many sandstone and siltstone outcrops and boulders (Photo 12).

Boulders, which have weathered for long periods of time, may exhibit a weathering rind which can be used to correlate the amount of weathering to time (Photos 13,14) (Birkeland, 1974). This rind is common in sandstone where porosity and permeability is high but does not experience extensive frost damage due to its high compressive strength and pore size (Winkler, 1975 and Walker, 1965). Weathered siltstone and sandstone boulders are generally blocky-shaped and in excess of 50 cm square.

Iron concretions which are common throughout the highwall section and spoil piles also exhibit a strong resistance to physical deterioration. The orange-red surface color results from oxidation of ferrous to ferric iron (Photo 15).

Coals show little evidence of physical or chemical weathering. Weathered fragments are blocky-shaped and surfaces often exhibit a duller lustre than fresh samples. Surface staining and deterioration of weathered coals is often due to weathering of impurities such as pyrite or shale bands contined within (Photo 16).

6.1.A Grain Size of Weathered Overburden

Table 6.1 illustrates rock particle sizes from the 0-100 cm depth of the overburden pile. Grain size results from this research are compared with those made by R. M. Hardy and Associates Ltd. (1974). These analyses reveal a lack of fine-sized particles within this depth range of overburden. Silt-clay sized rock particles comprise an even smaller proportion of this depth interval than were found within samples at 2010 cm depth. This decreased proportion of fines with depth indicates physical deterioration of rock occurs more slowly at depth than near the surface.

Table 6.1

Particle sizes within Grassy Mountain Spoil Pile (0-100 cm depth)

Particle Size (a)	(b)	(c)
Granule and greater	79.6%	91.0%
Sand	19.8%	9.0%
Silt-Clay	0.6%	0%

(a) Particle size based on Table 5.1
(b) Laboratory studies; U. of A., using U.S. Standard Sieves, Wentworth Scale 1978 (combination average bulk samples B1 and B2)
(c) R. M. Hardy and Associates Ltd.; 1974, Grassy Mountain Overburden

Table 6.2 reports the sieving results for the seventeen overburden samples. Samples 1-16 represent the 2010 cm depth range of the spoil pile, sample #17 represents the 0-2 cm portion. All samples reveal a lack of fine particles, as more than 86% of the total samples consists of rock particles equal to or greater than coarse sand, with sample #17 having

Table 6.2

GRAIN SIZE ANALYSIS: 2-10 cm DEPTH 5 cm
DIAMETER FRACTION: WEATHERED OVERBURDEN

GRAIN TYPE AND WEIGHT OF MATERIAL
WITHIN EACH SIZE FRACTION (GRAMS)

Sample #	Pebble	Granule	V.C. - C. Sand	M.V.F. Sand	Coarse Silt	M.-F. Silt Clay
1	223.7	147.1	343.1	124.2	10.2	1.1
2	250.3	202.7	287.6	131.3	12.5	4.4
3	326.0	177.7	218.4	101.8	13.7	5.9
4	409.3	152.0	230.6	108.8	11.8	1.9
5	317.8	201.6	342.8	133.3	13.7	7.4
6	150.5	177.3	312.1	108.7	10.4	4.0
7	184.9	126.1	206.0	76.9	9.3	1.6
8	164.0	184.8	326.5	110.5	7.9	3.2
9	221.6	205.6	423.5	128.4	9.3	2.9
10	145.7	210.6	354.9	127.1	12.1	4.4
11	380.9	268.6	200.3	62.0	2.5	0.6
12	171.8	177.9	279.2	122.7	9.1	2.7
13	392.6	286.6	244.1	17.2	0.4	0.2
14	262.5	173.0	246.0	102.5	9.8	4.1
15	272.4	178.4	256.5	132.4	7.1	3.0
16	261.1	163.8	328.0	101.5	8.8	2.3
*17	678.1	299.2	185.7	56.4	7.1	0.5
Total wt. (g)	4135.1	3034.0	4599.6	1689.3	148.6	49.7
Average wt.(g)	258.4	189.6	287.5	105.6	9.3	3.1
Mean % of total	30.3	22.2	33.7	12.4	1.1	0.4
Standard Deviation	86.75	41.2	63.2	30.97	3.6	1.9

*Sample #17 represents upper 2 cm of material from weathered overburden site at Grassy Mountain. It was not included in the cumulative calculations.

All samples sieved using U.S. standard sieves, samples oven dried prior to sieving and weighing Sample Grain Type according to Wentworth, J. Geol, 1922.

95% of its material larger than medium sized sand. The high proportion of coarse grained rock fragments in sample #17 is probably due to erosion of fine particles by wind and water.

6.2.B Specific Gravity

The bulk specific gravity of overburden samples #1-17 as reported in Table 6.3 indicate the presence of low specific gravity material (coal or coaly fragments) within each sample.

Table 6.3

SPECIFIC GRAVITY: 10 MESH PORTION OF WEATHERED
OVERBURDEN FROM GRASSY MOUNTAIN

Sample #	Bulk Specific Gravity
1	2.13
2	2.20
3	2.02
4	2.09
5	2.31
6	2.16
7	2.18
8	2.00
9	2.14
10	2.30
11	2.28
12	2.18
13	2.06
14	2.23
15	2.24
16	2.05
17	2.42
Average	2.16

Samples 1-16 taken from -2 10 cm depth from sample site on overburden pile.

Specific Gravity determined using method outlined in Soil Testing for Engineers; Lambe, T. Willians; M.I.T. John Wiley & Sons, Inc., 1951[70].

6.1.C Lithologies' Resistance to Weathering

Proportions of rock fragments trapped in boxes placed at the highwall's base are reported in Table 6.4 along with the relative occurrence of each lithology in the highwall. These percentages reveal the weatherability of each lithology relative to other lithologies present. Shale silty-shale units physically deteriorate quickly while sandstone units appear to be the most resistant lithologies to weathering at Grassy Mountain. Results indicated in Table 6.4, grain size analysis of rock fragments in the boxes and field observations were used to construct figure 6.1 which illustrates each lithology's resistance to weathering.

Table 6.4

% of lithology within collection boxes at highwall's base		% of lithology occuring within the highwall section	
Lithology	% of total	Lithology	% of total
Coal	5	Coal	9.3
Shale-Silty Shale	75	Shale-Silty Shale	53.4
Siltstone	15	Siltstone	12.6
Sandstone	5	Sandstone	34.7

6.2 Thin Section Description

Examinations of thin sections revealed that many alterations experienced by minerals and rock fragments during both artificial and natural weathering are similar.

6.2.A Weather Rind Thickness

Table 6.5 illustrates weathering rind thicknesses produced from 3-4 weeks of artificial weathering are very similar

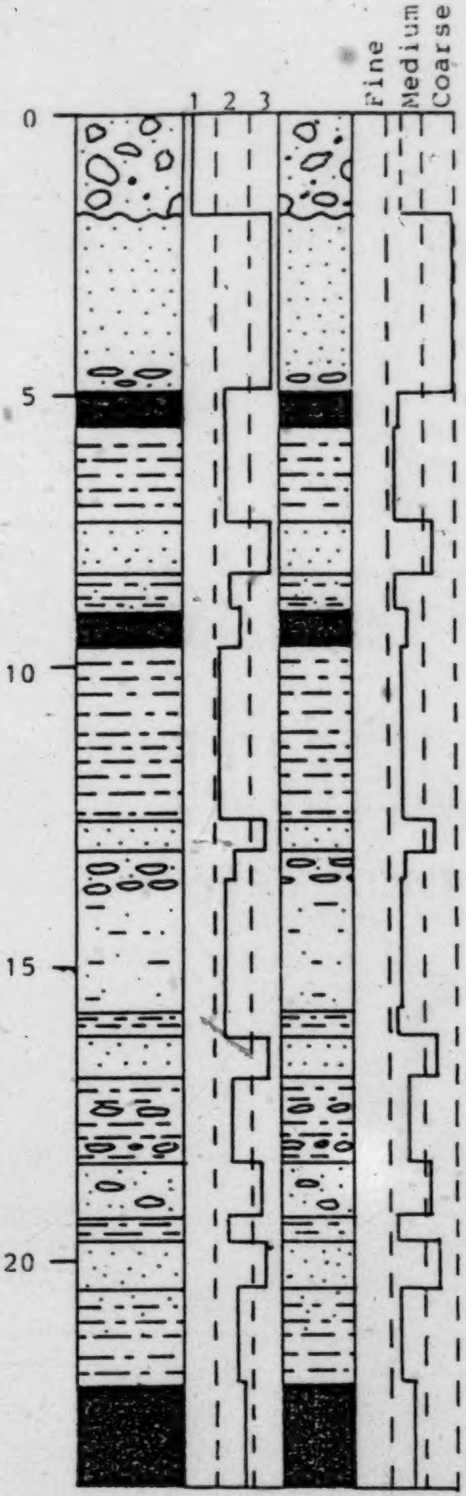


Fig. 6.1 **Grassy Mountain Rock Resistance to Weathering**

LEGEND

(A) Lithologies:

Till

Sandstone

Shale

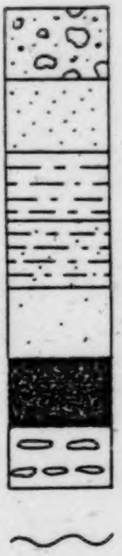
Silty Shale

Siltstone

Coal

Iron Concretions

Unconformity



(B) Resistance:

1 - Fine

2 - Medium

3 - Coarse

(C) Fragment Size

Fine - greater than 50% of weathered fragments are less than 3 cm.

Medium - 50% of weathered fragments are between 3 and 10 cm.

Coarse - more than 50% of weathered fragments exceed 10 cm.

to those exhibited by rock fragments which had undergone approximately 29 years of natural weathering. These results were plotted graphically and are represented in Appendix 7. These results alone do not provide absolute data for correlating the rate of artificial weathering over that of natural weathering because small differences in rind thickness on rocks at the end of a known period of weathering may represent significant differences in duration of weathering. (Ollier, 1969) Comparing rind thickness on specific sized particles from natural weathering environments to rinds on equal sized particles produced in an artificial weathering environment can be subject to error as only a small percentage of naturally weathered particles may have existed as the particular particle size throughout the total natural weathering period. Weathering rinds produced naturally must be observed frequently on the same samples over a long period to determine with certainty that the observed rind thickness at any point in time is a result of the known total duration of natural weathering. Similarities in rind thickness for similar lithologies from different weathering environments best indicate an equal amount of weathering.

6.2.B Thin Section Analyses of Weathering Upon Specific Lithologies from Grassy Mountain

6.2.B.1 Coal

Coal fragments which have undergone either natural or artificial weathering revealed little or no evidence of

Table 6.5

WEATHER RIND THICKNESSES FOR ARTIFICIALLY AND NATURALLY WEATHERED LITHOLOGIES FROM GRASSY MOUNTAIN

Sandstones		Siltstones		Shale	
Rind Thickness (mm)	Slide #	Rind Thickness (mm)	Slide #	Rind Thickness (mm)	Slide #
0.25	3	0.1	3	0.17	7
0.25	3	0.15	5	0.15	7
0.30	3	0.1	15	0.12	7
0.40	5	0.1	15	0.15	7
0.40	5	0.1	15	0.1	9
0.40	9	0.1	15	0.1	9
0.40	9	0.15	15	0.11	11
0.20	15	0.2	15	0.1	15
0.30	15	0.12	18	0.1	15
0.50	15			0.1	15
0.50	15			0.15	15
0.50	15			0.2	16
0.20	16				
0.20	16				
0.50	16				
0.50	16				
0.20	18				
0.20	18				
0.10	18				

Average Thickness of Weather Rinds

Lithology	(a) Thickness (mm)	(b) Thickness (mm)
Sandstone	0.34	0.31
Siltstone	0.13	0.13
Shale	0.15	0.13

(a) Artificially Weathered Samples Slides 1-14

(b) Naturally Weathered Samples Slides 15-18

See Fig. 1, 2, 3, Appendix 7; also Table 1, Appendix 7 for complete description of each slide.

physical or chemical weathering. Impurities present in some coal are responsible for the observed signs of weathering. The most obvious alterations are changes in surface lustre, color and the degree of fracturing. Weathered coal is duller and often exhibits reddish brown colors due to precipitation of iron oxides produced from the oxidation of sulphides and oxides contained within coal and shale inclusions. (Hackbarth, 1979)[25] Sulphides are present but rarely seen in the metallic state as most sulphur is organic. (Krouse, R., 1981)[32] Fracturing within weathered coal fragments was especially noticable in areas surrounding shaly inclusions, and increased with duration and intensity of natural and artificial weathering. Fracturing is mainly a result of differential volume changes and mineral expansion, within certain areas of the coal. Differential expansion within coal occurs in areas of "foreign" inclusions which are susceptible to wetting and drying, hydration, oxidation and freeze-thaw, ie. sulphides, oxides, clay minerals. (Rapson, J., 1963[58]; Ollier, C.D., 1969[52]; Birkeland, P.W., 1974[3])

It was not possible to distinguish between artificially and naturally weathered coal under a microscope. Physical deterioration of coal will occur most rapidly where there is an abundance of contained impurities. The presence of metallic and organic sulphides in the absence of calcerous material, such as observed in these coals, may result in acidic leachates as chemical weathering occurs.

6.2.B.2 Sandstone - Siltstone

Sandstone and siltstone have very similar mineralogical and structural characteristics and will therefore be discussed together.

Fresh samples of sandstone and siltstone display the colors of their mineral and rock constituents, ie. milky white to grey colors of quartz and feldspars, brown-tan tones of shale inclusions, carbonaceous material or oxides and black areas of coal or cherty fragments. Microscopic examinations of sandstones-siltstones revealed the following mineral assemblages.

Table 6.6 Average Mineral Assemblages Within Sandstones-Siltstones
Mutz Member, Grassy Mountain, Alberta

Major Minerals	%	Accessory Minerals	%	Cement	%
Quartz	40-60%	Oxides	1.0%	Siliceous	2-5%
Feldspar-Orthoclase	10-15	Sulphides	0.2	Calcareous (Calcite)	0-1
		Calcite Dolomite	1-4		
Chert	5-10	Apatite	0.2		
Rock Fragment	5-10	Muscovite	0.2		
		*Sericite, *Kaolinite	1.0		
		*Illite, Chlorite	1.0		

*Source (Rapson, J., 1963 MSc Thesis)

Quartz is the dominant detrital mineral followed by feldspars consisting of orthoclase and albite. Chert and shale fragments are very common and may comprise up to 10% of the specimen. In general, massive units contain less matrix than thinner laminated beds. Most matrix material consists of fine particles of the major minerals, as well as carbonaceous and amorphous clay material, illite, kaolinite and chlorite. (Rapson, 1963)[58]. The dominant cementing agent is amorphous silica that may be present up to 5% with carbonate cement, calcite occuring less frequently. Commonly carbonate cement fills secondary fractures within rocks and may comprise 4-5% of the total mineral assemblage.

Sandstone and siltstone experience similar weathering trends when exposed to either natural or artificial environments. The stained surfaces of sandstone or siltstone illustrate the most noticable signs of weathering. Sandstone and siltstone exposed to the atmosphere during weathering displayed greater amounts of surface precipitates than those buried within spoil piles or submerged under water. Sandstone commonly exhibits much deeper penetration of weathering (thicker rinds) which are lighter colored than those found on siltstone, experiencing similar durations and intensities of weathering. Deeper weathering in sandstone is due to its greater porosity and permeability than siltstone. Both massive siltstone and sandstone units at Grassy Mountain have high compressive strengths and can withstand physical and chemical degradation well (R. M. Hardy & Associates, 1975)[9]. Siltstone and sandstone containing shale partings, inclusions, fossils, or sedimentary features are susceptible to physical breakdown along these planes of weakness. Where spaces were large enough to allow penetration of water, natural weathering provided a disruptive force resulting in increased fracturing around concretions or shale fragments. Naturally weathered specimens experiences more physical deterioration than artificially weathered fragments.

Microscopic examination of these rocks confirms macroscopic weathering observations. Feldspar fragments showed increased fracturing and etching along mineral boundaries or fractures in both artificial and natural weathering environments. Feldspars are cloudy and commonly show minor alterations to sericite.

Calcareous cement fractures fillings, and grains consisting mainly of calcite with minor dolomite were highly weathered in samples exposed to either weathering environments.

Muscovite flakes commonly appeared cloudy and often covered by an amorphous material.

Quartz grains, chert fragments and siliceous cements appeared to be stable and exhibited only slight alteration. Etching of the siliceous cement which is 20 times more soluble than quartz grains was observed.

Chemical weathering of opaque minerals, ie. sulphides and oxides, by oxidation and hydration resulted in the formation of new minerals, the liberation of metallic ions and the production of sulphate ions. The alterations are visible due to staining on rock, mineral and matrix surfaces and by increased fracturing. Chemical weathering appears to occur on a larger scale in sandstones because of their greater porosity and permeability than siltstone.

Differences in weathered products from sandstone and siltstone subjected to both weathering environments is not obvious. The most noticable difference is a reduction of particle size in natural weathering whereas no fines were observed to be produced by artificial weathering.

Lower permeability of siltstone resulted in weathering rinds approximately half as thick as rinds produced on sandstone subjected to similar durations and intensities of weathering. Although siltstone weathering penetration depth was half that of sandstone, the finer grained texture exposed more mineral surface area (exchange sites) to the weathering environment. Leachates from siltstone should contain high initial ion concentrations exceeding that of sandstone initial leachates. The pH value of leachates from these two lithologies will probably be basic due to the weathering of carbonate minerals and the low sulphide mineral concentrations.

6.2.B.3 Shale

Shale subjected to natural weathering at Grassy Mountain exhibits rapid physical deterioration. The recessive nature results from their mineral assemblages, sedimentary structures, poor cementation and numerous other planes of weakness which allow penetration of moisture. Fracturing occurs by one or more of the following processes:

(1) Expansion of minerals due to water absorption into the crystal lattice (clay minerals).

(2) Wetting and drying effect (clay minerals).

(3) Collapse of mineral structure due to leaching or mineral alteration (iron oxides, sulphides, feldspars, mica).

(4) Expansion due to freezing.

Once a shale fragment is reduced to a size devoid of sedimentary structures, the rate of disintegration will decrease unless it contains a high proportion of clay minerals.

Thin section analysis of shale reveals a predominance of quartz grains in the silt size range resulting in the observed silty-shale texture.

Muscovite shards along with sericite commonly comprise up to 5% of the mineral assemblage. Feldspar, such as orthoclase and albite, are present in most samples occupying up to 10% of the rock. Opaque minerals consisting of iron oxides and more rarely, sulphides, were present in shale up to a maximum of 5%. Organic matter caused the darker brown color of shale. Amorphous material common to all shale examined was found to be illite, chlorite, kaolinite and organic matter. (Rapson, J., 1963)[58] The principal cementing agent is siliceous but calcite cement was also present in secondary fractures.

Weathered shale from both environments revealed signs of iron oxide and sulphide oxidating through staining. Feldspars were often etched and sericite occurred in the fractures and at the mineral boundaries. Muscovite and sericite shards were more strongly etched and altered in artificially weathered samples. Bregman (1976)[2] and Loughnan (1973)[42] found these minerals experienced rapid breakdown in hot humid environment but were stable in cold dry climates.

Two distinct zones are present in shale weather rinds. The first zone is an orange-brown to yellow brown region extending from the rock's surface inwards. Rocks and minerals within this zone are moderately to strongly altered. This outer zone terminated at a thin iron oxide crust which precipitated at the contact of "fresh" rock. This precipitate further reduces the permeability and inward penetration of chemical weathering in shale. The observed weathering rind in shale explains why "weather rind thickening decrease at an exponetial rate." (Ollier, 1969)[52]

Shale responds quickly to physical and chemical weathering, resulting in rapid physical deterioration. Opaque minerals alter rapidly when chemically weathered resulting in the liberation of many ions. The weathering of sulphides generates sulphate ions which often combine with Ca^{++} to form the commonly observed white calcium sulphate precipitates occurring on shale surfaces.

6.3 Analyses of Leachates

All tables of leachate chemistries are located in Appendix 4.

6.3.A Blanks

Results of the analyses of leachates produced within the soxhlet apparatus in the absence of rock samples are reported in Table 1. Calcium and magnesium concentrations were low or undetectable. Low concentrations of potassium cations were present in two leachates. Sodium cations occurred in each leachate with concentrations slightly higher in soxhlets containing cellulose thimbles. Silica was present in all four leachates. Each blank leachate was analysed to determine the concentration of Fe, Mn, Al, Ni, Pb, Zn, Cu but none of these metallic ions were detected.

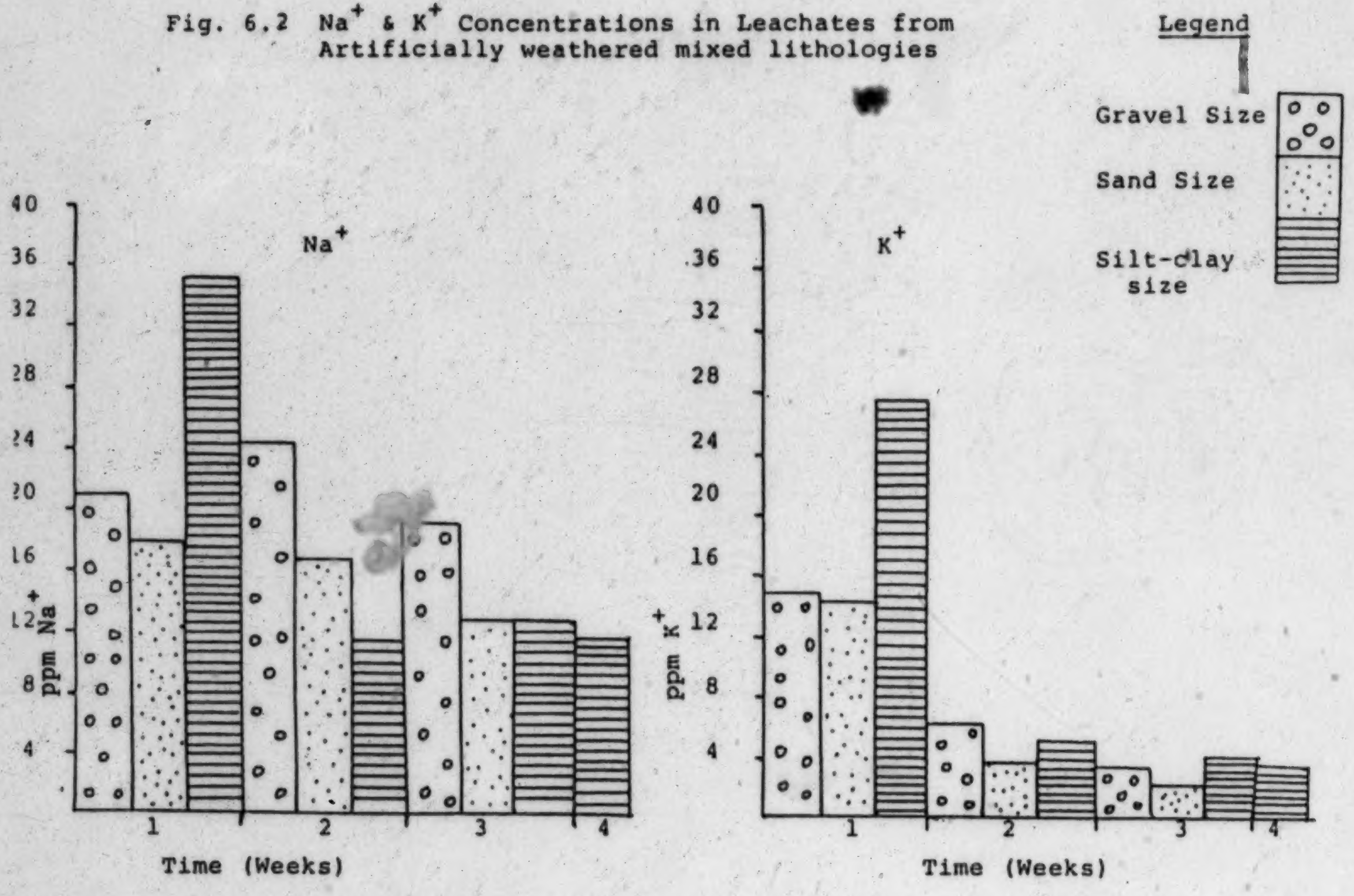
Sources of sodium, potassium and silica found in these leachates are from weathering of the soxhlet apparatus glass components. Results from the analyses of leachates derived from artificial rock weathering will be adjusted downward by the average concentration of sodium, potassium and silica observed in blank leachates.

6.3.B Leachates Derived From Artificially Weathering Mixtures of Specific Sized Rock Fragments

Results from the analyses of leachates derived from artificially weathering mixtures of granule, sand and silt-clay sized rock fragments are summarized in Tables 2 and 3 of Appendix 4, and Fig. 6.2.

Granule (gravel) sized particle leachates experience the least dramatic decrease in cation concentration with time. Calcium and sodium concentration increased during the second week of artificial weathering but began to decrease during the third week, indicating an evenly distributed source of these cations throughout the parent rock material. Magnesium concentration of granual leachates are low due to the absence of dolomite and other magnesium minerals. Potassium cations are abundant during initial stages of weathering but by the third week had decreased to one-fifth the initial con-

Fig. 6.2 Na$^+$ & K$^+$ Concentrations in Leachates from Artificially weathered mixed lithologies



centration.

Sand-sized particles produced leachates containing lower concentrations of cations, (excluding magnesium) than the coarser sized particles. A decline in cation concentration with time occurred for each cation with the exception of magnesium. This trend within sand leachates is expected, as the most accessible cations and unsatisfied bonds exist at the initiation of weathering. Calcium concentrations rapidly decreased between the first and second week then stabilized to a constant level. Sodium concentrations decreased at an increasing rate. Potassium concentrations dropped rapidly to less than one-third and one-seventh the initial concentration by the end of the second and third week respectively. Magnesium concentrations were low, but slighly more prevalent than in pebble sized fragments.

Silt-clay sized particle leachates yielded similar but more dramatic trends than observed from leachates of coarser sized rock fragments. Initial cation concentrations were greater than those observed in the coarser fragment leachates. By the second week of artificial weathering, cation concentrations had decreased by one-half to one-fifth of the first week's values. Three weeks of artificial weathering produced leachate concentrations of calcium and sodium lower than those observed after an equal duration of weathering for the two coarser sized rock groups. Magnesium concentrations were slightly higher in all leachates from silt-clay sized particles. Between the third and fourth week of artificial weathering only a slight decrease in cation concentration was observed within the silt-clay sized particle leachates. The pH of each leachate was 8.3, indicating that pH is not dependent upon rock particle size (Table 4).

Heavy metal concentrations in leachates derived from the three groups of particle sizes were low, sporadic and often undetectable. (Table 3). Artificial weathering of silt-clay sized particles yielded the highest concentration and greatest variety of metallic ions. Iron and copper were the most abundant metallic ions found within leachates. No lead was detected in any leachate.

Silica concentrations appeared to be related to particle size upon weathering of similar lithologies (Table 6). As particle size decreased the leachate concentration of silica increased. Silica concentration in silt-clay sized leachates was three times greater than gravel sized leachates.

Total alkalinity, bicarbonate, carbonate and sulphate concentrations of leachates representing each particle size are expressed in Table 5. Sulphate concentration increased as size of particle being weathered decreased. Total alkalinity, bicarbonate and carbonate concentrations of leachates does not appear to be related to size of rock particle weathered.

Trends observed in leachate analysis representing artificially weathered materials from three different sized rock particle groups yield "expected" observations. Crushing of rock produced unsatisfied bonds at the freshly broken rock and mineral surfaces, therefore initial weathering and leaching of cations, anions and metallic ions is rapid. As time and weathering progress, less unstable or unsatisfied bonds exist at rock and mineral surfaces. Chemical weathering penetrates inward to areas of more stable bonds, lower permeability, and porosity, therefore resulting in decreased rates of leaching. Silt-clay sized particles having the greatest mineral-rock surface area, per equal mass, of all sizes experimentarlly weathered will contain the highest initial concentration of soluble constituents in leachates and weathering will be rapid and complete. An environment dominated with stable bonds and characterized by low rates of weathering and leaching is quickly established in these fine grained particles. (Krauskoff, 1967[33]; Loughnan, 1962[40]; McConnel, 1951[46])

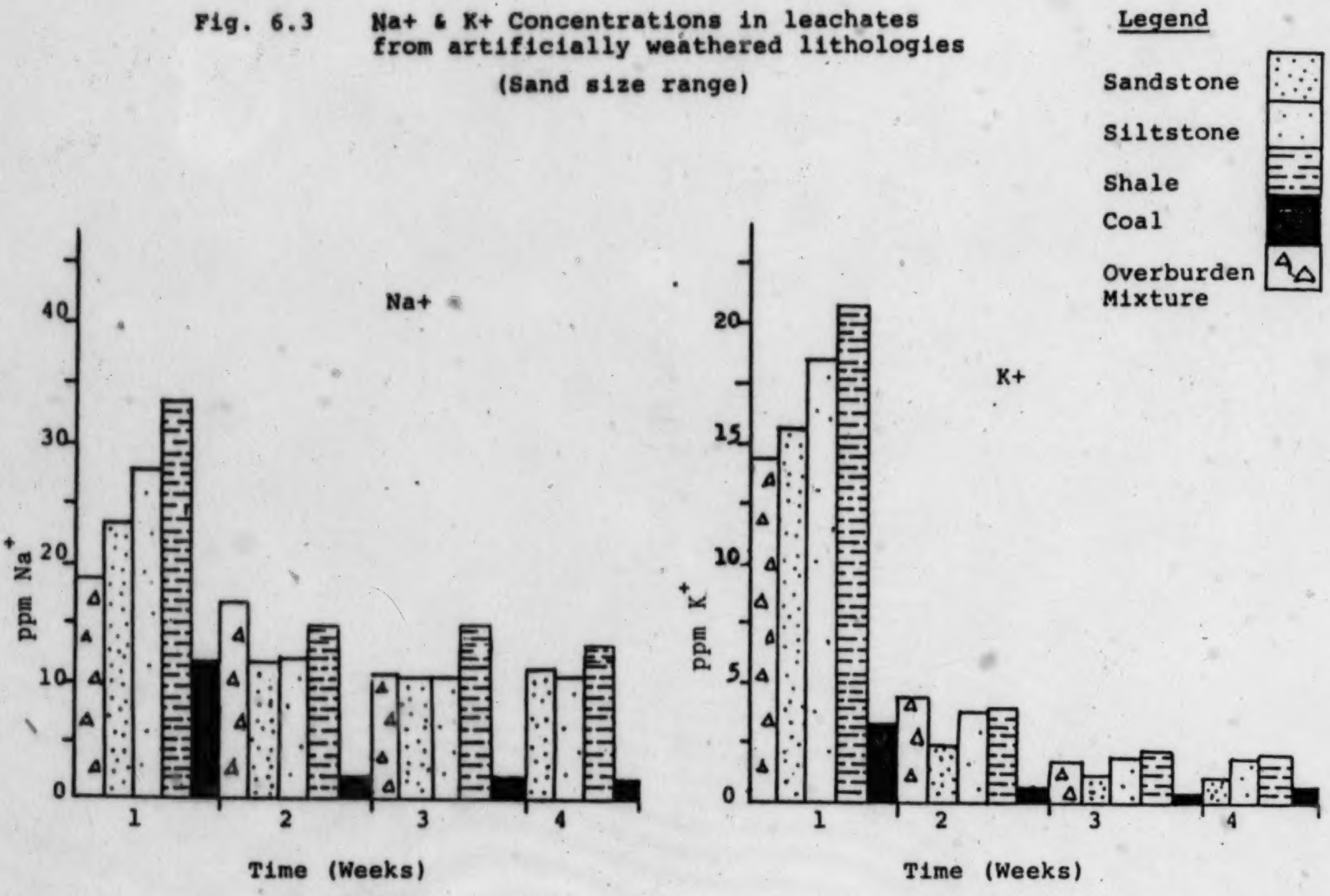
6.3.C Leachates Derived from Artificially Weathering Specific Lithologies

Two distinct groups of leachates were produced, those resulting from artificial weathering of multi-mineral rocks (sandstone, siltstone, shale) and those produced during artificial weathering of coal (Fig. 6.3, 6.4).

Multi-mineral rock leachates consisted of similar chemistry and concentrations. Calcium, sodium, and potassium cations had highest concentrations occurring during the first week of artificial weathering. These high concentrations dropped rapidly but by the third and fourth week only slight

Fig. 6.3 Na+ & K+ Concentrations in leachates from artificially weathered lithologies

(Sand size range)



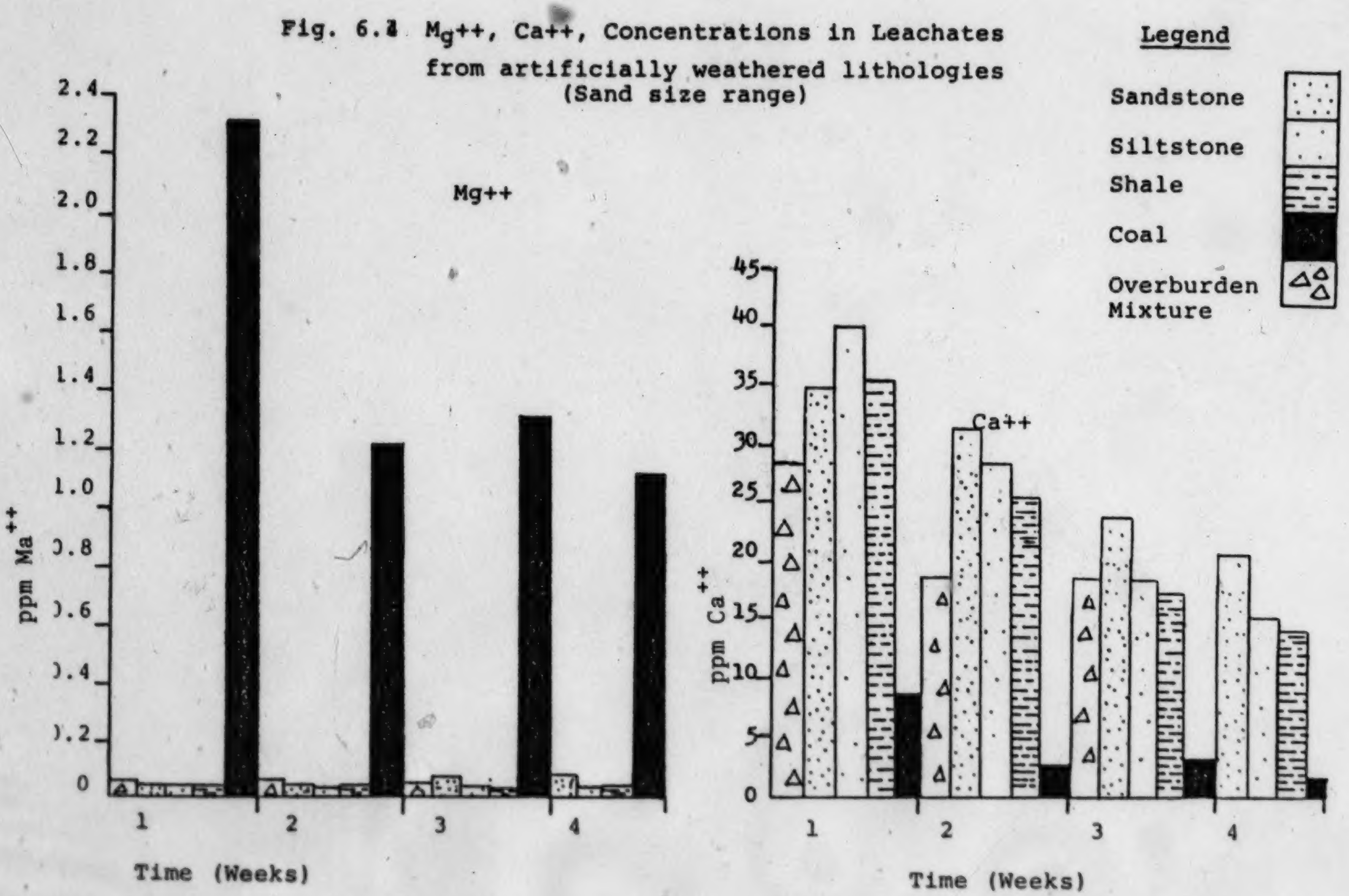


Fig. 6.2 Mg++, Ca++, Concentrations in Leachates from artificially weathered lithologies (Sand size range)

decreases in cation concentration within each group of leachates was observed. After four weeks of artificial weathering cation concentration reached a stable point. The remaining unweathered samples consisted of stable mineral bonds in equilibrium with the artificial weathering environment.

Magnesium cation concentrations in leachates produced from these three multi-mineral lithologic groups were low because of the absence of dolomite and magnesium minerals. Sandstone has the highest overall calcium cation concentrations. This results from sandstone's greater permeability and higher quantity of calcite than siltstones and shales. Leachates produced from weathering shales contained the highest initial, overall and final concentrations of sodium and potassium. This observation results from shale containing a greater proportion of minerals which contain accessible sodium and potassium cations, ie. clay and micaceous minerals.

Metallic ions in leachates produced from artificially weathering multi-mineral lithologies were in low, often undetectable, concentrations. Iron was present in trace amounts after one week of artificially weathering each lithology but was undetectable from this time on. Aluminum occurred in each leachate with a maximum concentration of 0.01 ppm occurring during the second week of siltstone and shale weathering. Copper, nickel, zinc and manganese occurred in each lithology's leachate but occurred as low concentrations. Lead was not detected in any of the leachates. Shale leachates yielded the greatest variety and highest concentrations of metallic ions. Sandstone leachates, with the exception of copper, yielded the lowest frequency and concentrations of metallic ions.

Silica concentrations in leachates were highest in shale, averaging 77.4 ppm over the four-week weathering period. PH values varied from pH = 8.1 to 8.4 for all leachates. Sandstone leachates from the first two weeks of weathering produced the most basic solutions.

Total alkalinity, bicarbonate and carbonate concentrations are similar for each lithology with sandstone leachates containing the highest initial concentrations of sulphate (Table 10). Sulphate ion concentrations in sandstone leachates declines below sulphate levels from siltstone and shale by th third week of artificial weathering. The high alkalinity and low sulphate concentrations from these leachates explains the basic pH values observed.

Leachates from soxhlet weathering of coal yielded a different and distinct chemistry from leachates of the other three lithologies. Coal leachates contain small amounts of calcium, sodium and potassium. The highest cation concentrations of calcium, sodium and potassium in leachates produced during the initial week of weathering coal are less than the lowest concentrations observed in leachates produced during the fourth week of weathering from the other three lithologies. Leaching of Na^+, K^+, and Ca^{++} from coal is very rapid and complete and after the initial week of weathering low, near stabilized concentrations of these cations are observed. Magnesium cation concentration in coal leachates is 185-1200 times higher than magnesium concentrations in sandstone, siltstone or shale leachates.

Leachates produced during the weathering of coals were acidic. Their pH values ranged from pH=5.0 to 5.4, becoming more basic as weathering progressed. These acidic leachates are nearing a level capable of mobilizing certain metallic ions, ie. aluminum.

The frequency and concentration of heavy metal ions observed in coal leachates was higher than in leachates representing the three other lithologies. No lead ions were detected in coal leachates.

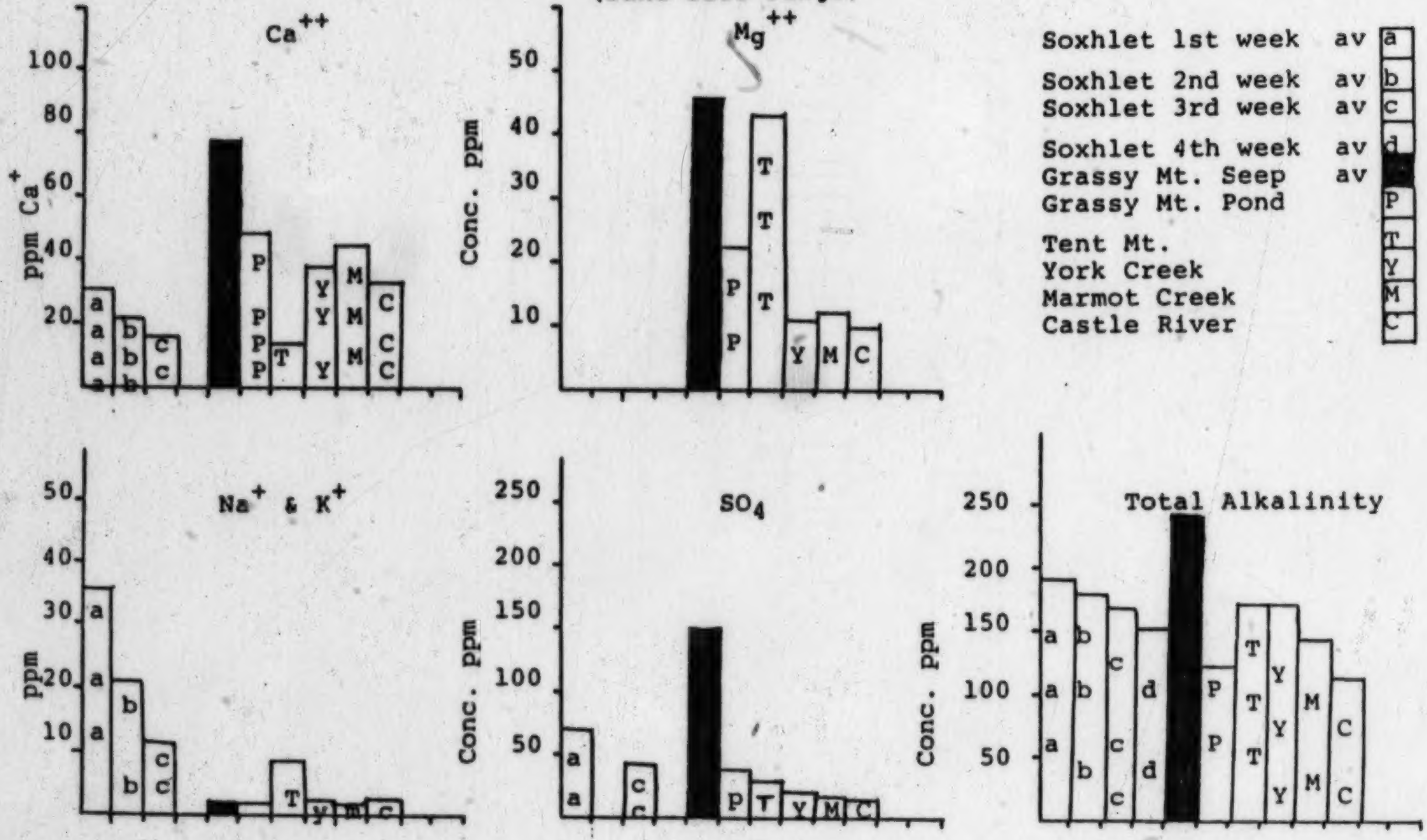
Total alkalinity, bicarbonate, carbonate and sulphate concentrations in coal leachates were lower than in the other three lithology leachates (Table 10). The pH of coal leachates were acidic ranging from 5.0 to 5.4. Acidic coal leachates result from a lack of carbonate minerals which buffer the hydrogen ions produced from weathering sulphides. Coal, weathering on its own may produce acidic leachates whose pH falls within a range capable of mobilizing metallic ions which remain immobile in more basic "normal" leachates, ie. Fe, Al, Zn, Pb.

6.3.D Analyses of Leachates Produced During Natural Rock Weathering

During the summer and fall of 1968 the Geological Survey of Canada sampled and analysed water emerging as seepages at the base of overburden spoil piles at Grassy Mountain, Tent Mountain and York Creek. Overburden at these locations has been subjected to natural weathering for 16-29 years, 0-29 years and 22 years respectively. Water samples from two other sources (Marmot Creek, Kananaskis Country and Castle River), which drain basins underlain by Kootenay strata with till veneers have been analysed and employed in these comparative studies. (Environment Canada 1961-1973) Marmot Creek basin has not been subjected to mining activity and therefore represents a stable natural weathering environment. Results of these analyses are presented in Tables 11 and 12.

Comparisons of natural and artificial leachates reveal that an increased duration of chemical weathering of rocks which have been rapidly physically broken down in size results in a lower amount of dissolved chemical constituents (Fig. 6.5). This is well illustrated when examining and comparing ion concentrations from the initial and final leachates produced during both artificial rock weathering and leachates derived from naturally weathered rock subjected to different duration of weathering. Ion concentrations in leachates will decrease as broken or unstable mineral bonds are weathered. The restoration of natural rates of physical deterioration will result in a slower more consistent rate of chemical weathering, subsequently ion concentration in leachates will stabilize. In order to establish the correct rate of acceleration of weathering in an artificial environment using identical samples and weathering agents, it is necessary to determine the leachates' stabilization point and the length of time needed to reach it.

Fig. 6.5 Concentrations of Elements in Leachates Derived from Artificial and Natural Rock Weathering (Sand size range)



The following conclusions may be drawn if Marmot Creek and Castle River represent stabilized areas of natural weathering:

(1) York Creek leachates indicate overburden is reaching a stabilized natural rate of weathering.

(2) Higher than "natural" ion concentrations in leachates from Tent and Grassy Mountains indicates overburden consists of rock with many fresh mineral surfaces. These concentrations will remain higher than normal but will decrease until natural rates of weathering occur.

(3) Fourth week leachates showed similar ion concentrations, to waters draining "stabilized natural weathering environments."

Magnesium and calcium cation concentrations in leachates from the two weathering environments were different because artificial weathering did not include any carbonate lithologies which were abundant in tills throughout the natural environment.

Sodium and potassium concentrations in fourth week artificial leachates were similar to Tent and Grassy Mountain leachates. These cation concentrations may be correlated as their source is similar.

Sulphate ion concentrations in artificial leachates were similar to those expressed in "stabilized" weathering environment. The alkalinity of fourth week leachates was lower than the alkalinity of natural leachates from stabilized areas.

With the exception of artificially weathered coal heavy metal ion concentrations in both natural and artificial leachates are low. The pH values of leachates from artificially and naturally weathered shale, siltstone, sandstone or mixtures of these with coal were similar.

Sampling of natural creek waters from Boisjole, Gold, and Blairmore Creek yielded leachate ion concentrations similar to those expressed above (Consol, 1975)[9]. Slight increases in iron, sulphate, bicarbonate and magnesium values were observed during low periods of flow in these creeks. A spring emerging from an abandoned mine shaft at Grassy Mountain contained high sulphate, sodium, calcium, magnesium and iron concentrations (Fe 18.9 ppm). These high concentrations were attributed to the mine water being acidic and having a low oxygen concentration. (Consol, 1975)[9].

CHAPTER 7

CONCLUSIONS AND DISCUSSION

Table 7.1 illustrates ratios between similar processes and products of natural verous artificial weathering.

On the basis of precipitation artificial weathering would be occurring 824 times faster than natural weathering. Higher temperatures within the soxhlet environment result in lower concentrations of dissolved oxygen and carbon dioxide. The lower dissolved oxygen in artificial rain is a significant retarding weathering factor and therefore the overall increased rate of artificial weathering caused by precipitation would decrease to approximately 206-412 times.

Temperatures within the soxhlet environment are 55-60°C higher than at Grassy Mountain resulting in artificial weathering occurring 185-600 times faster than in nature, (Van't Hoffs rule).

Corresponding lithologies exposed to 29 years of natural weathering and four weeks of artificial weathering produced weathering rinds and crusts of near identical thickness indicating similar amounts of weathering has occurred. These rinds suggest an artificial versus natural rate of weathering ranging from 330-375:1 (average 350:1).

Accelerated rates of artificial weathering based upon leachate concentrations may be determined by direct comparison of leachates produced from weathering overburden (natural and artificial) and leachates derived from local pristine waters draining from basins underlain by lithologies similar to the overburden. These comparisons were made and are expressed in Table 7.1 indicating artificial weathering rates were occurring 330-412 times more rapidly than in nature.

Table 7.1

ARTIFICIAL VERSUS NATURAL RATES OF WEATHERING

eathering Agent of Product	Natural Rate of Occurrence	Artificial Rate of Occurrence	Artificial: Natural Weathering Ratio
1 Precipitation	640 mm/yr[E]	52780 mm/yr	(824) 412:1
2 Temperature	5°-10°C[E] (126 days/year)	65°C (365 days/yr)	185:1 362:1 660:1
3 Weather Rind-Crust Thickness	Sandstone 0.0117 mm/yr	4.03 mm/yr	344:1
	Siltstone 0.0045 mm/yr	1.69 mm/yr	375:1
	Shale 0.0051 mm/yr	1.69 mm/yr	330:1
4 Leachate ion concentration (ppm)			
- Sodium	7.2[T] 0.8[G]	10.2[A]	
- Potassium	2.6[T] 1.2[T]	1.8[A]	337:1
- Sulphate	150[G]	12.8[B]	

E= Environment Canada 1973

A= 4 weeks' artificial soxhlet weathering (leachate)

B= 3 weeks' artificial soxhlet weathering (leachate)

T= Tent mountain, 0-29 years' natural weathering (leachate)

G= Average, Grassy Mountain. 29 years' natural weathering (leachate)

= Not correlatable.

NB= See Appendix 6.1 for further detailed calculations and results used in establishing Artificial:Natural weathering ratios.

The log of leachate concentrations vs. time may be plotted to predict the increased rate of artificial weathering and the time required for weathering overburden to produce leachate concentration similar to natural pristine waters. Log concentrations of sodium, potassium, sulphate and total alkalinity concentrations for each artificially weathered lithology were plotted. An average slope representative of each ion's concentration change with time was drawn. These curves were extrapolated until they reached the log concentration of similar ions from pristine leachates, ie. Mormot Creek and Castle River. Log concentrations from naturally weathered overburden were also plotted. Figures 7.1 and 7.2 revealed the following:

(1) Sulphate ion and total alkalinity concentrations of artificial leachates reached those concentrations found at mine sites and undisturbed streams within 3-4 weeks. Natural levels of sulphate and alkalinity are quickly reached in weathering overburden. The rate of artificial accelerated weathering was 300-400 times over natural rates.

(2) Potassium cation concentrations in artificially produced leachates decreases with time but at a rate slower than observed for sulphate ions and total alkalinity. Artificial weathering would have to progress 6 weeks to equal 29 years of natural overburden weathering and 8 weeks to achieve potassium concentrations similar to Mormot Creek or Castle River waters.

(3) Soxhlet weathering of overburden produced sodium concentration in leachates which slowly decreased with time. Sixteen to seventeen weeks of artificial weathering would be

required to produce leachates whose sodium concentrations were equal to the natural waters of Mormot Creek and Castle River.

(4) Soxhlet weathering indicates initial weathering of overburden will produce higher than normal concentrations of cations and anions. These high leachate concentrations will decrease rapidly during the first 5-10 years of natural weathering. After 10 years of overburden weathering leachate concentrations will approximate those of local pristine waters. The length of time required for each anion or cation concentration to stabilize at pristine values may be predicted from Figures 7.1 and 7.2 but may vary as the response to weathering for each mineral and mobilities of anions and cations will differ under similar weathering factors.

Soxhlet weathering has helped determine relative weathering rates and by-products of rock weathering. The following trends in chemical weathering of rocks were established from soxhlet weathering:

(1) Leaching of minerals occurs more rapidly for finer sized particles than in lithologically similar coarser particles. Fine sized leachate in concentrations decrease rapidly with time because weathering of rock samples is quick and complete.

(2) Particle size does not affect pH of leachates.

(3) Sandstone and siltstone composed of similar minerals are the most resistant lithologies to chemical and physical weathering. Their leachate concentrations vary slightly due to differneces in porosity and permeability but the variety and type of ions found within their leachates is similar. Shale

Fig. 7.1 Total Alkalinity and Sulphate Concentrations of Artificial, Natural Leachates and Prisitine Waters.

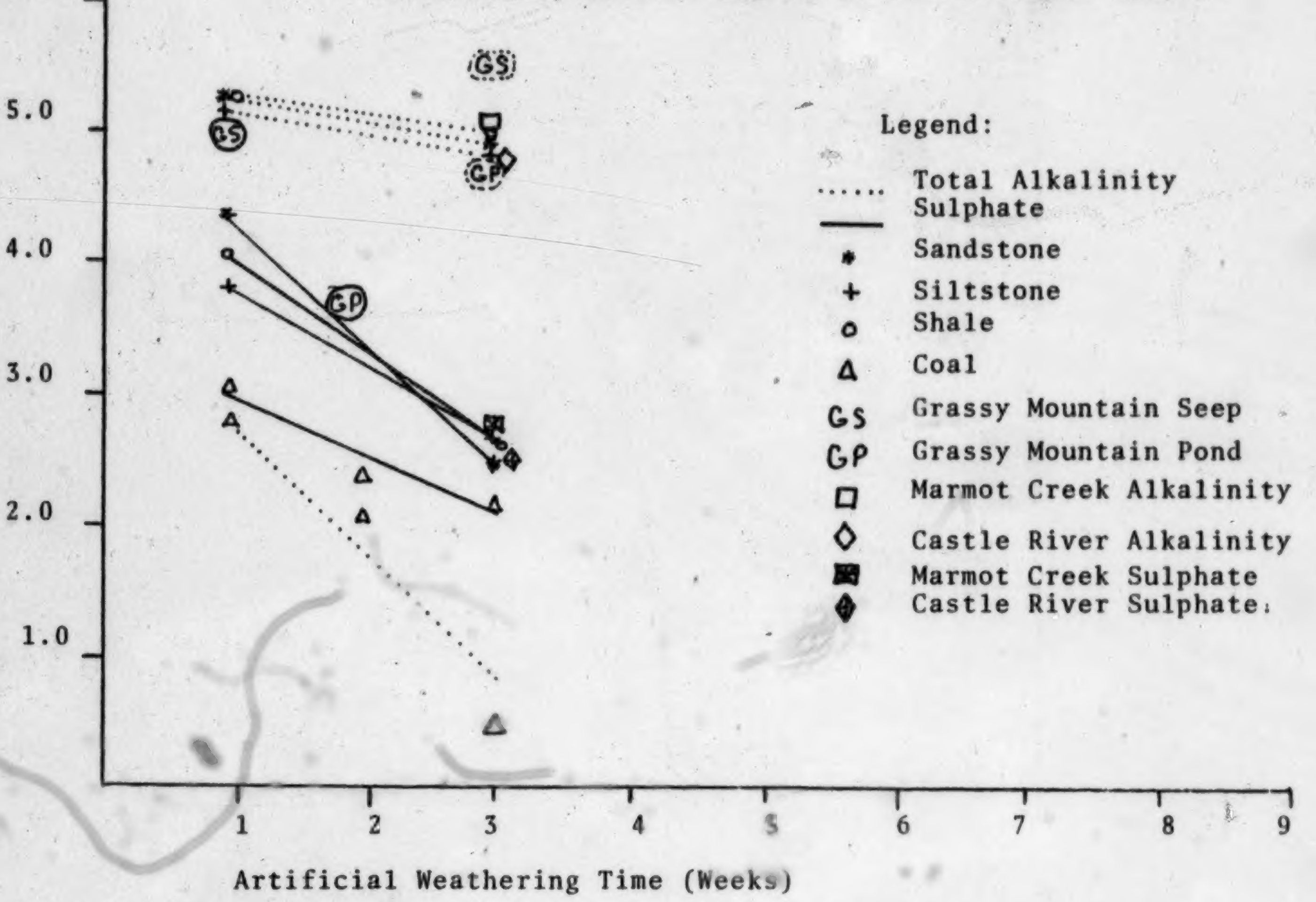
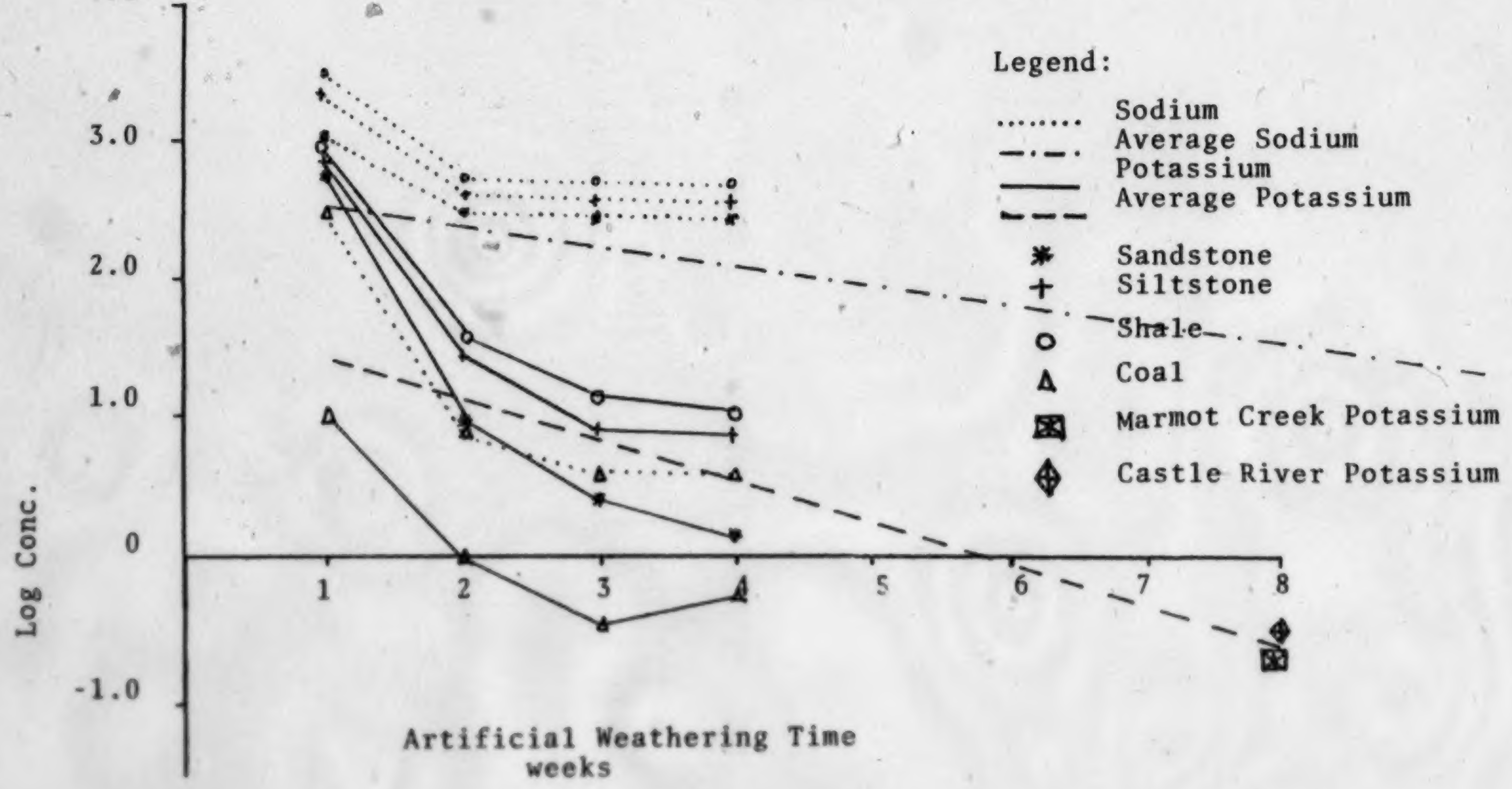


Fig. 7.2 Potassium, Sodium Concentrations from Artificial Leachates vs. Pristine Waters



contains a wider variety of minerals than sandstone and siltstone. Shale leachates therefore contain a greater variety of mineral ions than sandstone or siltstone leachates, and those ions common to all are often more abundant in shale leachates.

(4) The pH of leachates open to the atmosphere and derived from weathering siltstone, sandstone and shale is basic due to low sulphate and high bicarbonate concentrations. Coal leachates have lower sulphate and bicarbonate concentrations than sandstone, siltstone, or shale and their leachates are acidic especially during initial weathering stages.

(5) Weathering of coal possesses the greatest threat to the environment. To eliminate the risk of acidic leachates draining from open pit coal mine areas, coal and coaly shale should not be disposed without mixing with lithologies containing carbonate minerals.

Natural leachates emerging from weathering overburden associated with open-pit coal mines have recently been monitored by several researchers, (Hackbarth 1979, Jackson 1978, Harrison, 1977, Lavkulich 1979). Hackbarth sampled streams in the Grande Cache area which were in contact with weathering overburden and compared their chemistry to that of local pristine waters. Hackbarth noticed that the concentration of total dissolved solids of waters emerging from recently disposed overburden had increased by a factor of four but the ratios of cations to one another remained constant. Sulphate ion concentrations were independent of calcium concentrations indicating sulphate ions probably originated from the oxidation of sulphide minerals.

Sulphate concentrations increased at the expense of bicarbonate ions. Toxic elements present in Grande Cache leachates were within maximum permissable concentrations set by Environment Canada. All overburden leachates' pH fell between 7.6-8.2 which was normal for streams in the Grande Cache area. Hackbarth's results are consistent with those observed at Grassy Mountain and artificially produced Grassy Mountain leachates. An exception occurs in sodium concentrations which were higher than those from Kootenay overburden as Grande Cache overburden largely consists of Luscar sediment which contain sodic shales. Jackson, Harrison and Consol (R. M. Hardy and Associates) sampled waters from underground mine effluent, ponds occupying flooded open pits and springs below waste dumps in the Crowsnest Pass area of southwestern Alberta and southeastern British Columbia. Jackson noted that the concentration changes of major cations and anions in Kootenay dump drainage were greatest for calcium, magnesium and sulphate and not as dramatic for potassium and sodium cation changes which were observed by Hackbarth and soxhlet leachates. These trends were due to the age of the spoils that Jackson examined and variations in overburden chemistry. Soxhlet weathering indicated high initial sodium-potassium concentrations which rapidly decreases in approximately 1 week (5-10 years in nature) to near normal pristine concentrations. Jackson noted large increases in sulphate concentrations at the expense of bicarbonate and attributed this to rapid oxidation of sulphur compounds in the Kootenay Formation. Soxhlet weathering of these lithologies supported Jackson's observations. Jackson, Harrison and Consol found low heavy metal concentrations with the exception of iron and less frequently manganese. Low metallic ion concentrations reflect the physical and chemical weathering processes occurring within overburden and the chemistry of material being weathered. Consol observed iron concentrations of 18 ppm in waters emerging from underground mines at Grassy Mountain reflecting a reducing low oxygenated environment. Soxhlet weathering of similar lithologies produced equally low metal ion concentrations. Artificial and natural leachate pH from overburden in the Crowsnest Pass area was between 7.6 and 8.4 corresponding to the pH of local pristine waters. Only coal leachates from artificial weathering were acidic.

Lavkulich has artificially weathered spoils from open-pit coal mines in the Fernie Basin of southeastern British Columbia. Similar trends in leachate concentrations have been observed by Lavkulich as noted by Jackson, Hackbarth and Soxhlet weathering, ie. high initial concentrations of ions in leachates which rapidly decline stabilizing at near pristine water concentrations. Leachate pH remains alkaline, with the exception of coal and shaley-coal leachates.

Soxhlet weathering conducted on Kootenay overburden has produced leachate chemistries which correspond to other observations. In summary, cations and anions are lost most rapidly during the initial weathering of overburden due to the abundance of broken mineral bonds and fresh mineral surfaces at the rock surface. Within one week of artificial weathering (5-10 years natural weathering) many cation concentrations (ie. Na^+K^+) will have dropped 3-4 times. Weathering of overburden through time will produce leachates whose concentration more closely resembles pristine waters, however the length of time required for this to occur will vary with each ion.

Physical weathering of bedrock overburden has been investigated by several researchers, ie. Jackson, R. M. Hardy and Associates, Harrison and mining companies. Their observations and conclusions correspond with those made during this research. The following conclusions with respect to physical deterioration of bedrock can be drawn:

(1) There is a consensus that shale and silty-shale are the most susceptible to physical breakdown while sandstone-siltstone lithologies are resistant. Freeze-thaw and compressive rock strength tests on Kootenay lithologies support lithologies responses to physical deterioration (R. M. Hardy and Associates).

(2) Wetting-drying occurring at Grassy Mountain provides a significant disruptive force to the fine grained lithologies. Wetting-drying has not been investigated by other researchers working in this region but the frequency of its occurance is greater than that of freeze-thaw cycles. Physical weathering of shaley lithologies is observed during the warm summer months when frost-freeze is not occurring.

(3) Physical weathering of overburden lithologies is largely restricted to the upper 50 cm of spoil piles, below this all lithologies exhibit little or no visible breakdown and few particles less than 5% exist within the coarse sand size range.

Natural weathering of overburden will take many years to produce soils or an environment capable of sustaining plant growth. Chemical analyses of overburden has shown that shale contains sufficient nutrients for plant growth but natural weathering of these lithologies is slow and ions released during weathering are often carried away in solution (R. M. Hardy and Associates).

Reclamation of overburden at Sparwood was only successful while fertilizers were applied. Once this supply of nutrients was cut off vegetation disappeared. Overburden piles which incorporate till or local soils have a better success rate for revegetation. Overburden piles at Cardinal River Mines have grasses growing at the surfaces where till is abundant but are devoid of vegetation in areas of weathering bedrock. Spoil piles at Grassy Mountain have weathered 30 years and have only sporadic grass patches growing in sheltered areas, on till or soil, and weathered shale boulders.

Overburden spoils provide a harsh environment for plant growth. Surface temperature fluctuate daily and have been recorded to be in excess of 60°C, a temperature which would burn plant roots, (Harrison, Root, Theses Research). Soil moisture at spoil piles is low and the density of the overburden surface may be much higher than natural soils, inhibiting rooting of plants.

Natural soil development in the mountainous regions is slow. High elevations, where many open-pit coal mines operate, further reduce the rate of soil formation by retarding physical-chemical weathering rates. Investigations made during this research suggest natural soil development on overburden composed of bedrock will take several decades, more probably several hundred of years, to develop soil capable of sustaining plant growth.

To decrease the time required for overburden revegetation, till or local soils should be retained and placed at the surface or mixed well with bedrock overburden. Shaley lithologies deteriorate most rapidly and contain the greatest abundance of nutrients for plant growth, therefore these lithologies should be considered in reclamation. Unless a considerable quantity of till or soil is present in overburden, fertilizers will have to be applied for several years after reclamation.

Soxhlet weathering has provided a forecasting method to determine the rate of artificial weathering versus natural weathering. The accelerated weathering rate will vary for each study area but can be determined by studying natural weathering processes occurring within any specified area. Soxhlet weathering will enable a well planned open pit coal mine to properly dispose of its overburden, reducing the risk of producing acidic leachates which may mobilize toxic elements. A potential threat to water quality exists if overburden is not carefully analysed and properly disposed of. Artificial weathering within a soxhlet environment may be the time machine capable of predicting overburden weathering, water quality, soil development and reclamation problems associated with large-scale open pit coal mines.

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Appendix 1 - Climatic Records

Tables A1-A4 Temperatures

Tables B1-B6 Precipitation

Table A

Mean and Extreme Monthly Temperatures in the Crowsnest Pass Region, 1941-1970[a]

Table A1 - Mean Daily Temperature (°C)

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Coleman	- 8.1	- 5.9	- 3.4	2.4	7.3	10.8	14.5	13.5	9.3	4.9	- 1.6	- 6.1
Cowley	- 9.4	- 5.8	- 3.2	2.7	8.2	11.9	16.7	14.7	10.5	5.8	- 1.4	- 5.2
Lundbreck	-10.2	- 6.7	- 5.0	2.2	7.4	10.8	14.4	13.4	9.4	4.7	- 2.7	- 6.6
Ironstone (d)	-10.9	- 8.7	- 6.2	-0.5	4.5	7.4[b]	12.1[b]	11.2[b]	6.3[b]	2.1	- 4.4	- 8.9
Grassy Mt (d)	-10.9	- 8.7	- 6.2	-0.5	4.5	8.0	11.7	7.4[c]	5.3[c]	2.1	-4.4	- 8.9

Table A2 - Extreme Minimum Temperature (°C)

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Coleman	-37.2	-29.4	-32.8	-22.8	- 8.3	- 5.6	-2.2	-2.5	- 6.7	-15.5	-22.8	-41.1
Cowley	-40.6	-34.4	-30.0	-20.6	-11.1	- 3.8	-1.0	-1.0	-10.0	-19.4	-32.8	-43.3
Lundbreck	-45.0	-44.0	-40.0	-27.2	- 7.2	- 6.7	-3.8	-6.7	-22.2	-27.2	-37.8	-46.7
Ironstone (d)	-43.2	-35.4	-38.8	-28.8	-14.3	- 5.0	-3.5[b]	-2.0[b]	-12.2[b]	-21.5	-28.8	-47.1
Grassy Mt (d)	-43.2	-35.4	-38.8	-28.8	-14.3	-11.6	-8.2	-8.5	-12.7	-21.5	-28.8	-47.1

Source: (a) Environment Canada, 1973a; (b) Averages based on period, 1963-1970 (Stashko 1971a); (c) Consol, 1974-1975; (d) Calculated based on (Koeppe 1958, Barry 1970)

Table A

Mean and Extreme Monthly Temperatures in the Crowsnest Pass Region

1941-1970(a)

Table A3 - Extreme Maximum Temperature (°C)

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Coleman	10.0	13.9	16.7	22.2	26.7	29.4	30.6	33.9	31.1	22.2	13.3	9.4
Cowley	13.9	18.3	18.3	25.0	28.9	34.4	33.3	35.6	34.4	27.2	22.8	12.8
Lundbreck	18.3	17.2	19.4	28.0	32.8	34.4	37.2	35.0	36.1	28.3	21.7	17.2
Ironstone (d)	4.0	7.9	10.7	16.2	21.1	25.0[b]	25.3[b]	28.9[b]	26.1[b]	22.3	7.3	3.4
Grassy Mt (d)	4.0	7.9	10.7	16.2	20.7	23.4	24.6	27.9	25.1	22.3	7.3	3.4

Table A4 - Days with Frost for Specific Areas in the Crowsnest Pass Region, 1941-1970(a)

													Total
Coleman	29	26	26	21	13	4	1	3	8	14	24	29	198
Cowley	29	26	28	23	11	1	*	*	8	16	26	28	196
Lundbreck	30	27	30	26	19	7	3	5	14	24	27	30	242
Ironstone (d)	30	27	29	24	16	4	*	1[b]	10[b]	20	26	30	218
Grassy Mt (d)	30	27	29	24	16	12	*	4	12	20	26	30	223

Source: (a) Environment Canada, 1973; (b) Averages based on period 1963-70 (Stashko 1971a);
(d) Calculated values based on (Koeppe 1958, Barry 1970, Consol Reports 1975)

Table B

Monthly And Annual Total Precipitation in the Crowsnest Pass Region, 1941-1970[a]

Table B1 Mean Rainfall (mm)

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual (mm)
Coleman	4	4	3	14	54	72	34	48	37	24	17	6	317
Cowley	1	1	2	9	48	81	40	50	31	11	3	2	278
Lundbreck	0	Tr	Tr	9	45	97	45	52	31	7	1	1	288
Ironstone (c)	5	5	6	16	28[b]	119[b]	31[b]	43[b]	43	25	10	7	
Grassy Mt (c)	5	5	6	16	28	119	31	43	43	25	10	7	

Table B2 Mean Snowfall (cm)

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual (cm)
Coleman	42	31	25	32	8	1	0	0	5	12	30	36	222
Cowley	33	38	28	27	14	2	0	0	7	20	29	31	229
Lundbreck	24	29	34	39	12	2	0	5	13	17	29	27	231
Ironstone (c)	50	35	28	38	40[b]	1[b]	0[b]	5[b]	6	17	40	42	
Grassy Mt (c)	50	35	28	38	40	1	0	5	6	17	40	42	

Source: (a) Environment Canada, 1973b, (b) Averages calculated for period 1963-70, Stashko, (c) Estimates based on surrounding weather stations, generally 10-20% increase. Tr-trace.

Table B3 Mean Total Precipitation (mm)

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual (mm)
Coleman	46	35	29	45	63	72	34	48	43	36	47	41	539
Cowley	34	38	29	36	62	83	40	50	38	31	31	33	505
Lundbreck (c)	24	29	34	48	57	99	45	52	43	24	30	27	512
Ironstone (c)	55	40	34	54	68	120^b	31^b	48^b	49^b	42	54	49	640
Grassy Mt (c)	55	40	34	54	68	120	31	48	49	42	54	49	640

Source: (a) Environment Canada, 1973b, (b) Averages calculated for period 1963-70, Stashko, (c) Estimates based on surrounding weather stations, generally 10-20% increase. Tr-trace.

Table B4 No. of Days of Measurable Rainfall

													Annual
Coleman	1	1	1	4	8	11	6	7	6	5	4	2	56
Cowley	1	*	1	3	9	12	6	8	6	4	2	1	53
Lundbreck	0	*	*	1	7	11	6	8	4	1	*	*	38
Grassy Mt. (b)	0	1	1	4	8	12	6	7	6	5	4	2	56

Source: (a) Environment Canada, 1973b, (b) Calculate Values based on Koeppe, 1958; Barry, 1970.

Table B5 No. of Days of Measurable Snowfall

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Coleman	6	5	6	4	1	*	0	0	1	2	4	6	35
Cowley	9	9	9	7	3	*	0	0	2	4	7	8	58
Lundbreck	5	7	8	6	2	*	0	*	2	3	5	5	43
Grassy Mt (b)	8	8	8	7	3	1	0	1	3	4	5	7	55

Table B6 No. of Days of Measurable Precipitation

													Annual
Coleman	7	6	7	8	9	11	6	7	7	7	8	8	91
Cowley	10	9	10	10	12	12	6	8	8	8	9	9	111
Lundbreck	5	7	8	7	9	11	6	8	6	4	5	5	81
Grassy Mt (b)	8	9	9	11	11	13	6	8	9	9	9	9	111

Source: (a) Environment Canada, 1973b, (b) Calculate Values based on Koeppe, 1958; Barry, 1970.

Appendix 2 - Highwall Samples and Description

(1) Lithologic Description of Grassy Mountains Highwall

(2) Fresh Rock Samples Collected from the Highwall at Grassy Mountain

Detailed Lithologic Description of the Grassy Mountain Section

From field studies at Grassy Mountain the following scale, based on weathered rock fragment size, has been established to distinguish each unit's resistance to weathering.

(1) Fine - Greater than 50% of weathered material is less than 3 cm.

(2) Medium - Greater than 50% of weathered material is between 3 cm. and 10 cm.

(3) Coarse - Greater than 50% of weathered material is greater than 10 cm.

Unit No.

18 **Glacial Till**: 2-6 m. thick, clastic sediments and coal fragments are dominant, carbonate eratics common, Crowsnest Volcanics sparsley scattered throughout. Matrix consists of finer fractions of above lithologies.

Kootenay Formation
Mutz Member

Thickness Meters

17 **Sandstone**: cement predominately silicous and minor calcareous; fresh color, light brown weathering to rusty brown, grains well sorted with quartz being dominant, fine to medium grain size (Wentworth). 3.1

Unit No.	Kootenay Formation Mutz Member	Thickness Meters
17 (cont'd)	Massive unit with silty laminations which are easily eroded. This unit forms a ledge, is resistant and weathered fragments are coarse, angular and blocky.	
16	Coal: bright, blocky, marcasite flecks present less than 0.5 mm. Weathered fragments 2-5 cm., medium.	0.6
15	Shale: carbonacious, calcareous and limonitic, silty bands brown colored, shale areas black colored. Quartz grains compose silty fraction. Fractures common parallel and perpendicular to laminations. Plant fossils common in shale areas. Laminations and fossils are the areas of most rapid weathering. White percipitate on surface as well as iron staining. Silty areas more resistant to weathering than shaley areas. Weathered fragments 3-5 cm., rubbly to flaky; medium.	1.7
14	Sandstone: Fine grained with silty laminations. Silicious cement, light brown when fresh, weathering to rusty-orange brown. Iron staining is very pronounced. Ripple	0.9

Unit No.	Kootenay Formation Mutz Member	Thickness Meters
14 (cont'd)	marks and fine laminations present in lower portion, upper half is massive. Ledge forming resistant unit. Weathering mainly occurring along laminations or silty-sandy contacts. Weathering to blocky coarse fragments.	
13	Shale: finely laminated silty areas present. Black when fresh, weathering to brown-orange, brown indicating presence of iron. Plant fossils present. Unit thickens to the northwest. Weathering most prominent along laminations, fossil plains, and bedding yielding flaky, angular, fine fragments.	0.6
12	Coal: bright, blocky, marcasite flecks present on coal's surface, medium-sized angular fragments produced during weathering.	0.6
11	Shale: finely laminated at base, massive in upper areas, silty layers present. Black, weathering to rusty brown. Iron stains common, white percipitate present on weathered surface. Plant fossils common. Recessive unit, weathering occurs most rapidly along	3.0

Unit No.	Kootenay Formation Mutz Member	Thickness Meters
11 (cont'd)	laminations and fossil plains. Weathered fragments flaky, 1-2 cm., fine.	
10	Sandstone: fine grained, well sorted, quartz grains, siliceous cement, light brown weathering to slight rusty brown. Very resistant unit, weathered fragments are blocky, coarse.	0.5
9	Siltstone: argillaceous throughout, iron concretions numerous in upper meter of unit. Brown weathering to rusty brown with bright orange surfaces around concretions. Laminations and fine bedding common within this unit. Silt and siliceous cement help to make this unit more resistant than shaley unit, fragments weather to medium-sized angular blocks.	2.8
8	Shale: carbonaceous, shaley unit. Black color both fresh and weathered. Fine laminations throughout. Very recessive unit, weathered to fine, flaky, platy fragments.	0.4

Unit No.	Kootenay Formation Mutz Member	Thickness Meters
7	Sandstone: calcareous and limonitic. Salt and pepper texture. Siliceous and calcareous cement. Grey weathering to light brown. Well sorted with an abundance of quartz grains. Crossbedding, ripple marks and sill bands are present. Pyrile grains present with stained aureols surrounding them on weathered surfaces. Massive areas are more resistant to weathering than laminated or crossbedded areas. Weathered fragments are blocky medium size.	0.8
6	Shale: grades upward to silty shale, black weathering to brown-black. Iron concretions approximately 3 cm. in upper portion. Laminations present throughout. Shaley sections less resistant than silty-iron concretion section. Unit is recessive, shale weathers to flat platy shapes, silty areas weather to rubbly shaped, fine size fragments.	1.4
5	Sandstone: fine grained, fine laminations limonitic, carbonaceous. Brown weathering to yellow-brown, fractures common parallel to laminations, quartz grains predominate, siliceous	0.9

Unit No.	Kootenay Formation Mutz Member	Thickness Meters
5 (cont'd)	cement. Iron concretions present throughout. Unit shows resistance to weathering, iron staining common, material weathers to blacky fragments 6-8 cm., medium size.	
4	Shale: silty and fossiliferous. Finely laminated, fractured, very recessive. White percipitate on weathered surface. Laminations and fossil plains form plains of weakness. Quickly weathers to flaky fine-sized material.	0.4
3	Sandstone: carbonaceous, calcareous and siliceous cement. Grey weathering to brown tones. Ripple marks, crossbedding, calcite filled fractures, iron staining common. Resistant ledge forming unit, weathers to blocky, coarse fragments.	0.9
2	Shale: silty, fossiliferous, carbonaceous calcareous. Black weathering to dark grey. Fine laminations present. Recessive unit, silty areas most resistant. White percipitate on surface. Weathers to flat, thin flakes of fine size.	1.7

Unit No.	Kootenay Formation Mutz Member	Thickness Meters
1	Coal: bright, blocky, marcasite flecks present on the surface. Weathers to blocky fragments of medium size. No. 2 seam base of Mutz member. Principle coal seam extracted during open pit mining.	1.7

Table 2

Fresh Lithologic Samples From Grassy Mountain Highwall Section

Group A

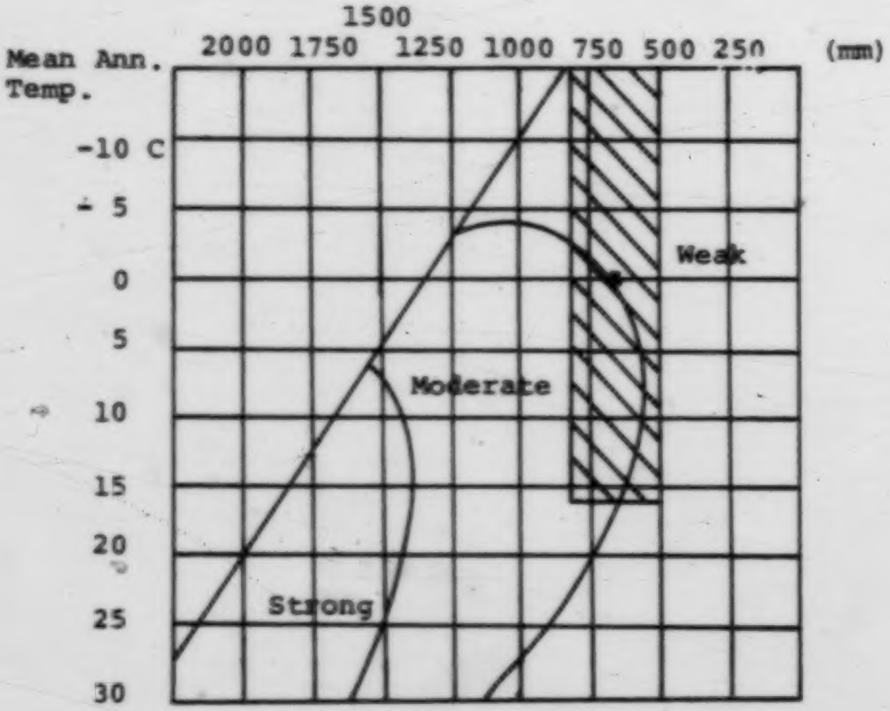
Sample #	Unit #	Lithology
G8681	1	Coal, #2 seam, upper 1 -2 m
G8682, G8682A	2	Shale, Silty Shale
G8683	3	Sandstone
G8684	4	Shale
G8685	5	Sandstone
G8686	6	Shale
G8688	7	Sandstone
G8689	8	Shale
G86810	9	Siltstone
G8687	10	Sandstone
G86811, G86811A	11	Shale
G86816	12	Coal
G86812	13	Shale
G86813	14	Sandstone
G86814, G86815	15	Shale, Silty Shale
G86816A	16	Coal
G86817	17	Sandstone
G86818	18	Glacial Till

Appendix 3 - Effects of Climate on Rock Weathering

Figure 1 - Effect of Temperature and Precipitation Upon Chemical Weathering

Figure 2 - Effect of Temperature and Precipitation Upon Physical Weathering

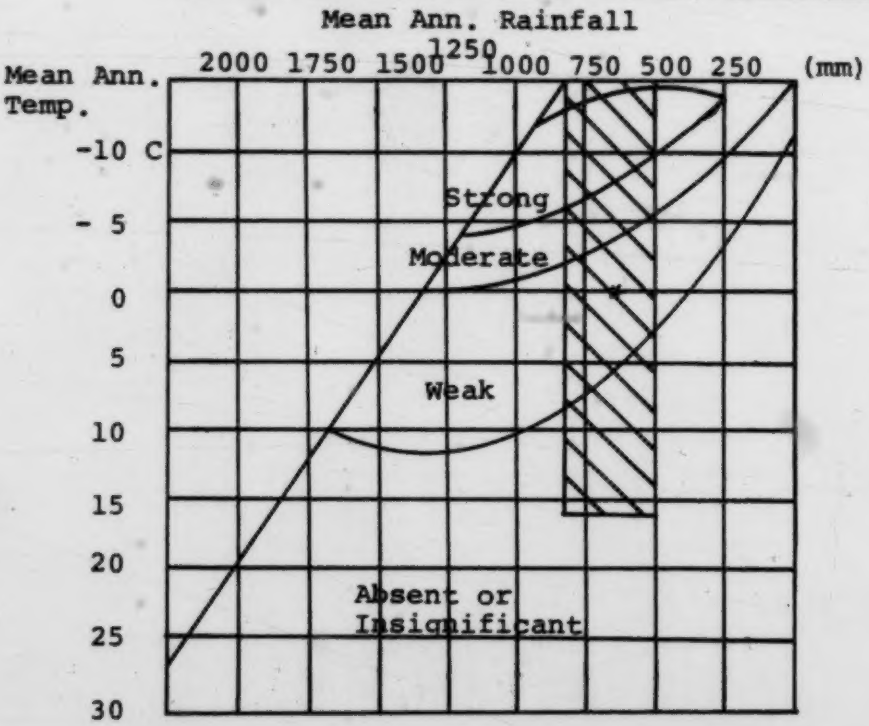
Fig. 1
Effect of Temperature and Precipitation Upon Chemical Weathering



Intensity of chemical weathering increases with an increase in temperature and precipitation. (Modified after Peltier, 1950). Ollier C.D., Weathering, Oliver and Boyd 1969.

Environment at Grassy Mountain. * Normal; Range \\\

Fig.2 Effect of Temperature and Precipitation Upon Physical Weathering, ie: Frost Action



Intensity of frost weathering in relation to rainfall and temperature. (Modified after Peltier, 1950). Ollier C.D., Weathering; Oliver and Boyd 1969.

Environment at Grassy Mountain. *Normal; Range \\\

Appendix 4 - Leachate and Water Analysis

Table 1 - Blank Leachate Analysis

Table 2 - Changes in Cation Concentrations with Time in Leachates Produced from Soxhlet Weathering of Various Particle Sizes

Table 3 - Heavy Metals, Trace Elements and Toxic Materials Found Within Leachates Produced by Soxhlet Weathering of Samples Representing Various Particle Sizes

Table 4 - Change of pH for Artificially Weathered Samples

Table 5 - Total Alkalinity, Bicarbonate, Carbonate and Sulphate Concentrations of Leachates Produced from Three Groups of Artificially Weathered Overburden

Table 6 - Silica Concentrations in Leachates Produced During Artificially Weathering Three Groups of Specified Particle Sizes Representing Grassy Mountain Overburden

Table 7 - Heavy Metals, Trace Elements and Toxic Materials Found Within Leachates Produced by Soxhlet Weathering of Samples Representing Specific Lithologies

Table 8 - Changes in Cation Concentrations with Time in Leachates Produced from Soxhlet Weathering of Various Lithologies

Table 9 - Silica Concentrations in Leachates Produced During Artificially Weathering Sandstone, Siltstone, Shale and Coal

Table 10 - Total Alkalinity, Bicarbonate, Carbonate and Sulphate Concentrations of Leachates Produced During Artificial Weathering of Grassy Mountain Sandstone, Siltstone, Shale and Coal

Table 11 - Water Chemistry of Leachates Derived from Natural Rock Weathering

Table 12 - Water Chemistry of Seeps (Springs) Emerging at the Base of Overburden Spoils at Grassy Mountain

Table 1

Blank Leachates

Leachate #	Concentration (ppm)						
	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Si	Al	pH
1	Nd	Nd	2.2	Tr	40.2	Nd	6.5
2	Nd	0.04	3.2	0.3	25.7	Nd	6.5
3	Nd	Nd	5.0	0.17	15.0	Nd	6.5
4	Nd	0.05	6.5	0.04	30.4	Nd	6.5
5*	Nd	0.02	4.2	0.13	27.8	Nd	6.5

Duration of weathering for each sample for 1 week.

Samples 1 and 2 produced in the absence of a cellulose thimble;

Samples 3 and 4 produced in the presence of a cellulose thimble

*average concentrations and pH values

Table 2

Changes in Cation Concentrations with Time in Leachates Produced from Soxhlet Weathering of Various Particle Sizes

Particle Size	Duration of Weathering (Weeks)	Cation Concentration (ppm) Ca^{++}	Mg^{++}	Na^{+}	K^{+}
Granual	1[a]	33.6	0.03	20.7	14.7
	2[b]	34.6	0.02	24.7	6.2
	3[c]	24.3	0.02	19.9	3.2
Sand	1[b]	27.5	0.04	18.4	14.0
	2[b]	18.5	0.04	16.5	4.3
	3[b]	18.3	0.06	12.4	2.1
Silt Clay	1[c]	46.8	0.07	35.5	27.5
	2[c]	28.4	0.05	11.6	5.7
	3[c]	18.1	0.05	12.4	4.0
	4[c]	17.6	0.04	11.8	3.7

a from five leachates of equal mass samples and similar duration of weathering

b from six leachates of equal mass samples and similar duration of weathering

c. from two leachates of equal mass samples and similar duration of weathering

Table 3

Heavy Metals, Trace Elements and Toxic Materials found within Leachates produced by Soxhlet Weathering of Samples Representing Various Particle Sizes

Sample	Duration of Weathering (weeks)	Element Concentration (ppm)						
		Al	Fe	Cu	Ni	Zn	Pb	Mn
Granual Size	1[a]	Tr	0.15	0.002	Tr	0.003	Nd	0.001
	2[b]	Tr	0.02	0.001	Nd	Nd	Nd	Nd
	3[b]	Nd	Nd	Nd	Nd	Nd	Nd	Nd
Sand Size[b]	1	Nd	Tr	0.001	Tr	Tr	Nd	Nd
	2	Nd	Tr	0.001	Nd	Tr	Nd	Nd
	3	Nd	Tr	Nd	Nd	Nd	Nd	Tr
Silt-Clay Size[c]	1	Nd	Tr	0.005	Nd	Tr	Nd	Nd
	2	Nd	Nd	Nd	Tr	Nd	Nd	Nd
	3	0.02	0.01	Nd	Tr	Nd	Nd	Nd
	4	Tr	Nd	Nd	0.01	Nd	Nd	Nd

Note (1) Average values determined for each set of data using the following number of leachates; a=5, b=6, c=2.

(2) Nd=not within detection range of the atomic absorption apparatus.

(3) Tr=Trace, less than 0.001 ppm except Al and Fe where Tr represents values less than 0.01 ppm (calculated using concentration factor and A.A. detection limits, Butler and Kokot, 1971).

Table 4

Change in pH of Artificially Weathered Samples Leachates with Time

Sample	Duration of soxhlet weathering period (weeks) and pH of leachate produced at the termination of each period.			
	Time 1 pH	Time 2 pH	Time 3 pH	Time 4 pH
Sandstone[a]	8.4	8.4	8.3	8.3
Siltstone[b]	8.1	8.2	8.2	8.2
Shale[c]	8.2	8.2	8.2	8.2
Coal[d]	5.0	5.0	5.2	5.4
Granual Size	8.3[e]	8.3[f]	8.3[f]	
Sand Size	8.3	8.3	8.3	
Silt-Clay Size[g]	8.2	8.3	8.3	8.3

Note: (1) Initial pH of double distilled water in each situation was 6.5 which is the neutral point of water at 65 C.

(2) Number of samples used to determine average pH of each leachates; a=1, b=1, c=1, d=3, e=5, f=6, g=2.

Table 5 Total Alkalinity, Bicarbonate, Carbonate and Sulphate Concentrations of Leachates produced from 3 Groups of Artificially Weathered Overburden

Sample (Particle size)	Duration of Weathering (weeks)	Total Alkalinity	Bicarbonate	Carbonate	Sulphate
Granual	1	122	149	2.7	26
	3	188	227	nil	9.6
Sand	1	189	230	nil	69
	3	166	202	nil	41
Silt-Clay	1	95	115	3.0	93
	3	105	128	nil	15.1

Table 6 Silica Concentrations in Leachates Produced During Artificially Weathering 3 Groups of Specified Particle Sizes Representing Grassy Mountain Overburden

Sample Size	Duration of Weathering (Weeks)	Silica Conc. (ppm)	Average Silica Conc. (ppm)
Granual	1	27.8	
	2	37.5	
	3	23.4	29.6
Sand	1	30.1	
	2	31.6	
	3	51.5	37.4
Silt-Clay	1	79.5	
	2	97.2	
	3	111.2	
	4	108.2	99.2

Table 7

Heavy Metals, Trace Elements and Toxic Materials found within Leachates produced by Soxhlet Weathering of Samples Representing Specific Lithologies

Sample	Duration of Weathering (weeks)	Element Concentration (ppm)						
		Al	Fe	Cu	Ni	Zn	Pb	Mn
Sandstone	1	Nd	Tr	0.003	Nd	Tr	Nd	Nd
	2	Tr	Nd	0.04	Tr	Nd	Nd	Nd
	3	Tr	Nd	Nd	Nd	Nd	Nd	Nd
	4	Nd	Nd	Nd	Nd	Nd	Nd	Nd
Siltstone	1	Nd	Tr	0.003	Nd	Nd	Nd	Tr
	2	0.01	Nd	Nd	Nd	Nd	Nd	Nd
	3	Nd	Nd	Nd	Nd	Nd	Nd	Nd
	4	Nd	Nd	Nd	0.005	Nd	Nd	Nd
Shale	1	Nd	Tr	0.003	Tr	Tr	Nd	Nd
	2	0.01	Nd	0.02	Nd	Nd	Nd	Nd
	3	Nd	Nd	Nd	0.01	Nd	Nd	Nd
	4	Nd	Nd	Tr	0.005	Nd	Nd	Nd
Coal	1	0.5[illegible]	Tr	0.014	Nd	0.001	Nd	Tr
	2	0.47	0.013	0.002	Nd	Nd	Nd	Tr
	3	0.24	0.03	0.002	Nd	Nd	Nd	0.002
	4	0.17	0.04	0.02	Nd	Nd	Nd	0.005

Note (1) Nd = not within detection range of the atomic absorption apparatus

(2) Tr = Trace of element, less than 0.001 ppm except for Al and Fe where Tr represents values less than 0.01 ppm. (calculated using conc. factor and A.A. detection limits, Butler and Kokot, 1971].

Table 8

Changes in Cation Concentration with Time in Leachates Produced from Soxhlet Weathering of Various Lithologies

Lithology	Duration of Weathering (weeks)	Cation Concentration (ppm)			
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}
Sandstone	1	34.8	0.03	21.5	14.9
	2	33.0	0.04	12.2	2.6
	3	24.7	0.07	11.9	1.4
	4	21.4	0.07	13.1	1.2
Siltstone	1	39.0	0.03	26.8	18.2
	2	29.0	0.02	12.7	4.1
	3	18.7	0.04	12.2	2.5
	4	15.1	0.04	11.8	2.5
Shale	1	34.9	0.04	32.9	20.1
	2	24.7	0.03	14.8	4.6
	3	17.5	0.02	14.7	3.2
	4	14.5	0.04	14.0	2.6
Coal	1	8.4	2.4	12.7	2.8
	2	3.2	1.5	2.4	1.0
	3	4.0	1.5	1.8	0.6
	4	1.7	1.3	1.8	0.8

(a) Each sample 50 g

Table 9 Silica Concentrations in Leachates Produced During Artificially Weathering Sandstones, Siltstones, Shales and Coals from Grassy Mountain.

Sample	Duration of Weathering (Weeks)	Silica Concentration (ppm)	Average Silica Concentration (ppm)
Sandstone	1	61.0	
	2	70.4	
	3	61.0	
	4	65.7	64.5
Siltstone	1	56.3	
	2	70.4	
	3	68.0	
	4	70.3	66.3
Shale	1	70.4	
	2	79.7	
	3	77.4	
	4	82.0	77.4
Coal	1	28.2	
	2	Nd	
	3	Nd	
	4	Nd	7.0

Table 10 Total Alkalinity, Bicarbonate, Carbonate and Sulphate Concentrations of Leachates Produced During Artificial Weathering of Sandstone, Siltstone, Shale and Coal from Grassy Mountain.

Sample	Duration of Weathering (weeks)	Total Alkalinity	Bicarbonate	Carbonate	Sulphate
Sandstone	1	207	252	nil	80
	3	139	169	nil	11.9
Siltstone	1	197	240	nil	67
	3	130	158	nil	13.2
Shale	1	206	251	nil	59
	3	136	166	nil	13.1
Coal	1	16.9	20.6	nil	21.5
	2	8.5	10.4	nil	12.1
	3	1.7	2.0	nil	9.1

Analyses conducted by United Petro Laboratories, Calgary, Alberta (1979).

Table 11 Water Chemistry of Leachates Derived from Natural Rock Weathering

Weathering at Grassy Mountain and Similar areas in the Crowsnest Area

Water Chemistry	Grassy Mountain Seep (Av)[a]	Grassy Mountain Pond (Av)[b]	Tent Mountain[c]	York Creek[c]	Marmot Creek[d]	Castle River[d]
pH	8.1	8.1	8.5		8.2	
Total Alkalinity	253	125	168	168	149	110
Mg^{++} (Diss)	45.3	21.2	41.2	12	12.4	9.6
K^+ (Diss)	1.2	1.2	2.6	1.3	0.5	0.6
Ca^{++} (Diss)	78.5	47.5	10.0	38	45.3	33.0
Na^+ (Diss)	0.8	0.8	7.0	0.8	1.5	2.4
SO_4^- (Diss)	150.0	47	22.0	20.0	17.0	13.6
Si (Diss)	4.3	2.2	6.0			
Al (Diss)	0.031	0.019	0.006			
Fe (Diss)	0.05	<0.04	<0.04			
Mn (Diss)	<0.01	<0.01	<0.01			

(a) Average of 4 samples, 1978 Geological Survey of Canada.

(b) Average of 2 samples, 1978 Geological Survey of Canada.

(c) Geological Survey of Canada, 1978.

(d) Water Quality Data, Alberta 1961-1973, Environment Canada.

Table 12 Water Chemistry of Seeps Emerging at the base of Overburden Spoils at Grassy Mountain

Grassy Mountain Seeps (Photo 4.3)

Water Chemistry (ppm)	June 22/78	July 25/78	Aug 25/78	Oct 29/78	Average
Water Temp. (°C)	6.2	8	13	6	8.2
pH	8.1	7.7	8.5	8.1	8.1
Total Alkalinity	210	206	234	362	253
Magnesium (Diss)	47.2	44.5	46.8	42.7	45.3
Potassium (Diss)	1.1	1.4	1.1	1.0	1.2
Calcium (Diss)	80.6	84.5	78.8	69.9	78.5
Sodium (Diss)	0.7	0.8	0.8	0.9	0.8
Sulphate (Diss)	170.0	170.0	150.0	110.0	150.0
Silica (Reactive)	3.9	4.2	4.4	4.5	4.3
Aluminum (Diss)	<0.075	<0.006	<0.005	0.038	0.031
Iron (Diss)	0.06	0.04	0.04	0.05	0.05
Manganese (Diss)	<0.01	<0.01	<0.01	<0.01	<0.01
Copper (Diss)				0.002	
Zinc (Diss)				0.003	
Lead (Diss)				<0.004	

Analyses made by Environment Canada for the Geological Survey of Canada.

Appendix 5

Table 1 - Summary of Grassy Mountain Compressive Rock Strength Test

Table 2 - Commonly Used Classification of Particle Sizes

Table 3 - Grain Size Scales

Table 4 - Proportions of Grassy Mountain Lithologies to be Artificially Weathered

Table 5 - Porosities and Permeabilities of Various Rock Groups

Table 6 - Sensitivity, Detection Limits, Analytical Range of Specific Elements Using the Perkin-Elmer Atomic Absorption Spectrophotometer

Table 1

Summary of Grassy Mountain Compressive Rock Strength Tests

Rock Type	No. Samples	Approximate Compressive Strength	Average Density (gm/cc)
Conglomerate	7	17,000 psi	2.57
Siltstone	30	13,800 psi	2.63
Altered Siltstone (brittle, hard, fine grain)	10	20,400 psi	2.58
Sandstone (banded samples showed greater strength)	14	16,900 psi	2.60
Shale (Some samples grade into siltstone but they are not included in this group)	5	11,900 psi	2.60

Source: Water Quality and Chemistry Vol. III Grassy Mountain
1975; R.M. Hardy and Associates for Consol. Coal

Table 2

Commonly Used Classifications of Particle Sizes

Wentworth Scale		U.S. Dept. of Agriculture		International Grade Classes	
Grain Type	**m.m.***	**Grain Type**	**m.m.***	**Grain Type**	**m.m.***
Granual	2	Stones	2.0		
Very Coarse Sand	1-2	Gravel	1-2		
Coarse Sand	0.5-1		0.5-1	Coarse Sand	2.0-0.2
Medium Sand	0.25-0.5		0.25-0.5		
Fine Sand	0.12-0.25		0.25-0.10	Fine Sand	0.2-0.02
Very Fine Sand	0.12-0.062		0.10-0.05		
Silt	0.062-0.002		0.05-0.002	Silt	0.02-0.002
Clay	0.002		0.002	Clay	0.002

*Grain diameter determined by standard sieves; silts and clays by sedimentation and Stoke's Law.

Source: Carroll, Dorothy; Rock Weathering, Plenum Press, 1970.

Table 3

GRAIN SIZE GRADE SCALE(a)

Mesh(b)	m.m.	Grain Type(c)
	256-4,096	Boulder
	64-256	Cobble
5 Up	4-64	Pebble
6-10	4-2	Granule
12-18	2-1	V.C. Sand
20-35	1-0.5	C. Sand
40-60	0.5-0.25	M. Sand
60-120	0.25-0.125	F. Sand
120-170	0.125-0.088	V.F. Sand
	Microns	
170-230	88-62.5	V.F. Sand
230-325	62.5-44	C. Silt
	44-3.9	M., F., V.F., Silt
	3.9	Clay

(a) Modified from Nat. Res. Council Rept. Comm. Sedimentation, 1941 (essentially Wentworths' scale, J. Geol., 30 377-392 (1922).

(b) U.S. standard mesh retained on.

(c) V.C., very coarse; C., coarse; M., medium; F., fine; V.F., very fine.

Source: Modified from Scientific Methods in Analyses of Sediments, Griffiths J., McGraw Hill Book Co., 1967.

Table 4

Proportions of Grassy Mountain Lithologies to be Artificially Weathered

Combined sample weight = 500 gr.

A) Total weight and volume of each lithologic constituent

Lithology	% Total Volume	% Total Weight	Weight (gr)
Sandstone	34.7	36.4	182
Siltstone	12.6	13.3	66.5
Silty-Shale	26.6	27.9	139.5
Shale	16.8	17.7	88.5
Coal	9.3	4.7	23.5

Table 5

Porosities and Permeabilities of Various Rock Groups

	Porosity %		Relative Permeability
Granite	1	Igneous	1
Basalt	1	Igneous	1
Shale	18	Shale	5
Limestone	10	Limestone	30
Sandstone	18	Sandstone	500
Gravel	25	Gravel	10000
Sand	35	Sand	1100
Silt	40	--	--
Clay	45	Clay	10

Source: Ollier, C.D., Weathering, Oliver and Boyd, 1969.

Table 6

Sensitivity, Detection Limit, Analytical Range of Specific Elements Using the Perkin-Elmer Atomic Absorption Spectrophotometer

Element	Wavelength[b] A	Detection[a] Limit (ppm)	Sensitivity[a] ppm	Analytical Range[b] ppm
Zinc	3076	0.001	0.001[a]	up to 2.0[a]
Lead	2833	0.5[b]	0.5	up to 5.0
Copper	3248	0.005	0.09	up to 5.0
Iron	2483	0.1	0.12	up to 5.0
Manganese	2795	0.05	0.55	up to 3.0
Aluminum	3093	0.9	1.0	up to 50.0
Silicon	2208	0.9	0.06	up to 300
Calcium	4227	0.03	0.08	up to 5.0
Magnesium	2852	0.005	0.007	up to 0.5
Sodium	5890, 5896	0.01	0.015	up to 1.0
Potassium	7665	0.03	0.04	up to 2.0
Nickle	2320	0.1[b]	0.15	up to 5.0

(a) Source, Butler, L.R.P.; Kokot, L.; Atomic Absorption, Modern methods of Geochemical Analyses, 1971

(b) Perkin-Elmer Atomic Absorption Spectrophotometer Manual, 1978

Appendix 6 - Plates

Photographs 1-16

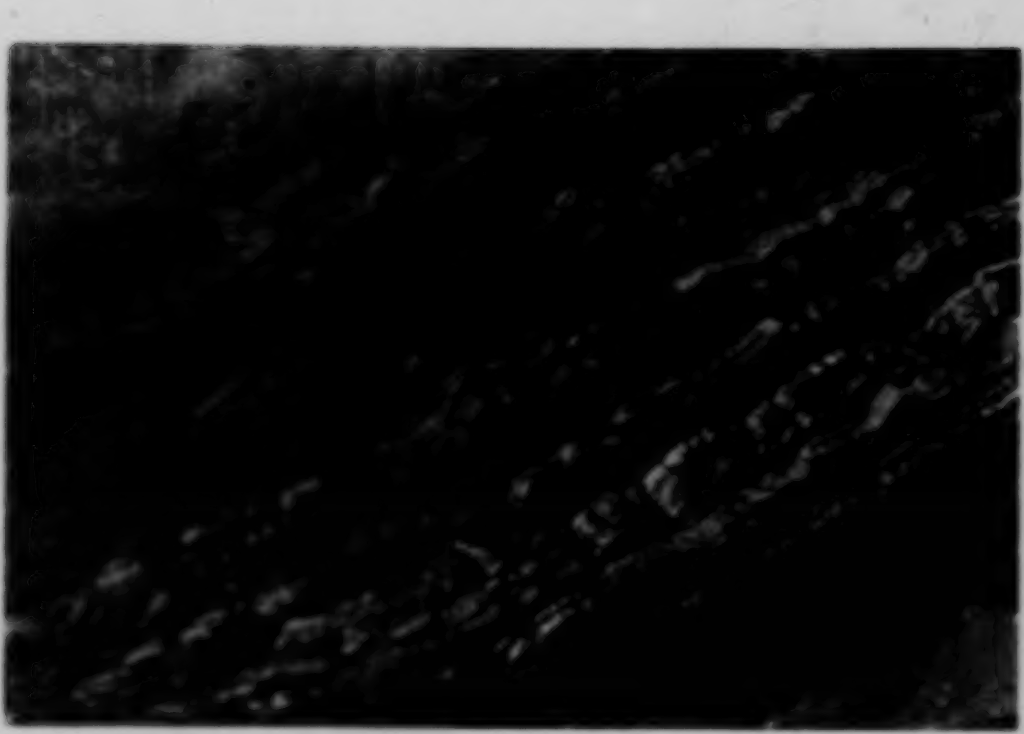


Plate 1 - Highwall Section of Grassy Mountain

Plate 2 - Open pit V-shaped trench, highwall section on the left

Plate 3 - Springs emerging from overburden at base of highwall section and open-pit trench

Plate 6 - Comparison of Lithologies' resistance to physical weathering.

Large Shale boulder, top, rapidly deteriorates to small platy fragments. Coal fragment, middle left, remains intact, its surface exhibiting a lustre duller than that of a fresh sample. Sandstone boulder, middle right, shows minor fracturing along blast induced micro-fractures and bedding planes. Iron-oxide coating covers the sandstone boulder (Chemical weathering). Duration of weathering approximately 29 years.

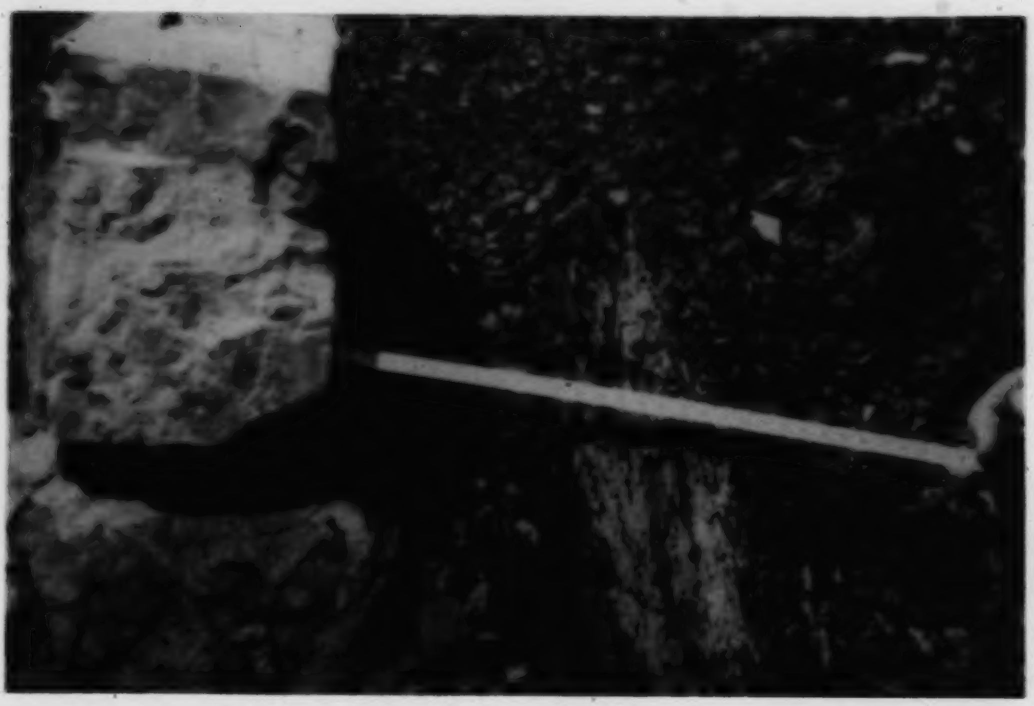


Plate 5 - Comparison of Lithologies' resistance to Physical Weathering

Shale, middle right, extreme physical destruction due to weathering. Silty-shale, bottom left, moderate physical breakdown. Sandstone, minor physical deterioration, iron-oxide coating (Chemical Weathering). Duration of weathering, approximately 29 years.

Plate 6 - Weathered shale boulder with interbed of siltstone. Note - Siltstones'resistance to weathering w.r.t. shale. Duration of weathering approximately 29 years.

Plate 7 - Oxidation of iron on silty-shale units (orange-red). Calcium sulphate precipitate on shale surface (upper 1/3). Duration of weathering approximately 29 years.

Plate 8 - Calcium sulphate precipitate on shale surface at the highwall section. Duration of weathering approximately 29 years.

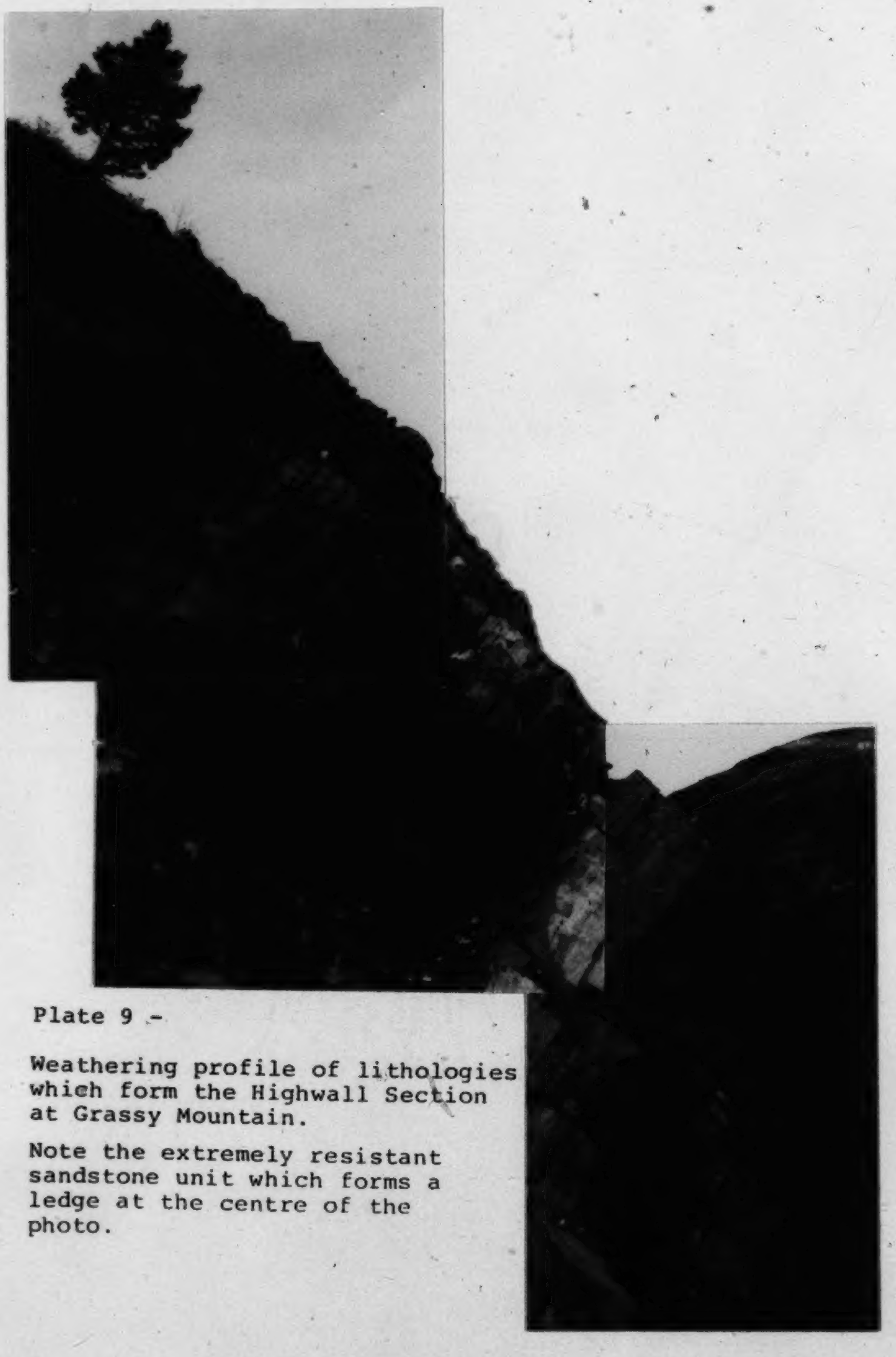


Plate 9 -

Weathering profile of lithologies which form the Highwall Section at Grassy Mountain.

Note the extremely resistant sandstone unit which forms a ledge at the centre of the photo.

Plate 10 - Upper portion of highwall section. Massive Sandstone units, #1, appear very resistant to physical breakdown. Coal seam, #2, appears much more resistant than shale, silty-shale units, #3. Duration of weathering approximately 29 years.

Plate 11 - Oxidized sandstone boulder with interbed of shale. Duration of weathering approximately 29 years.

Plate 12 - Surface oxidation of ferrous iron on sandstone boulders. Duration of weathering approximately 3-5 years.

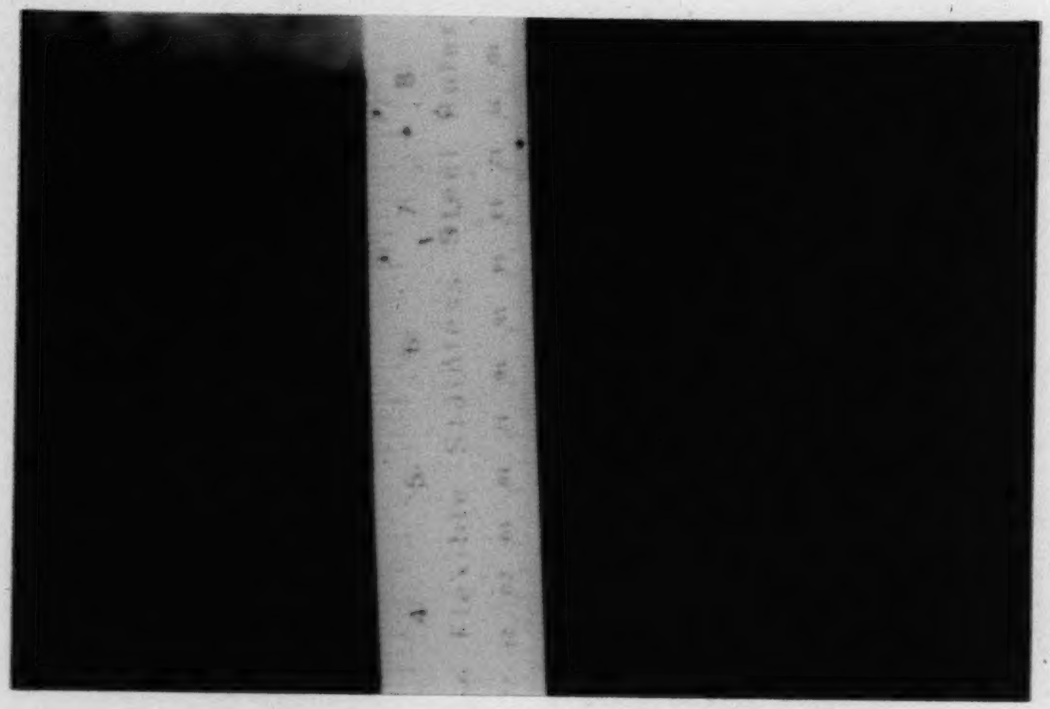


Plate 13 - Weathered Sandstone boulder. Oxidation rind approximately 2.5cm thick. Duration of weathering approximately 29 years.

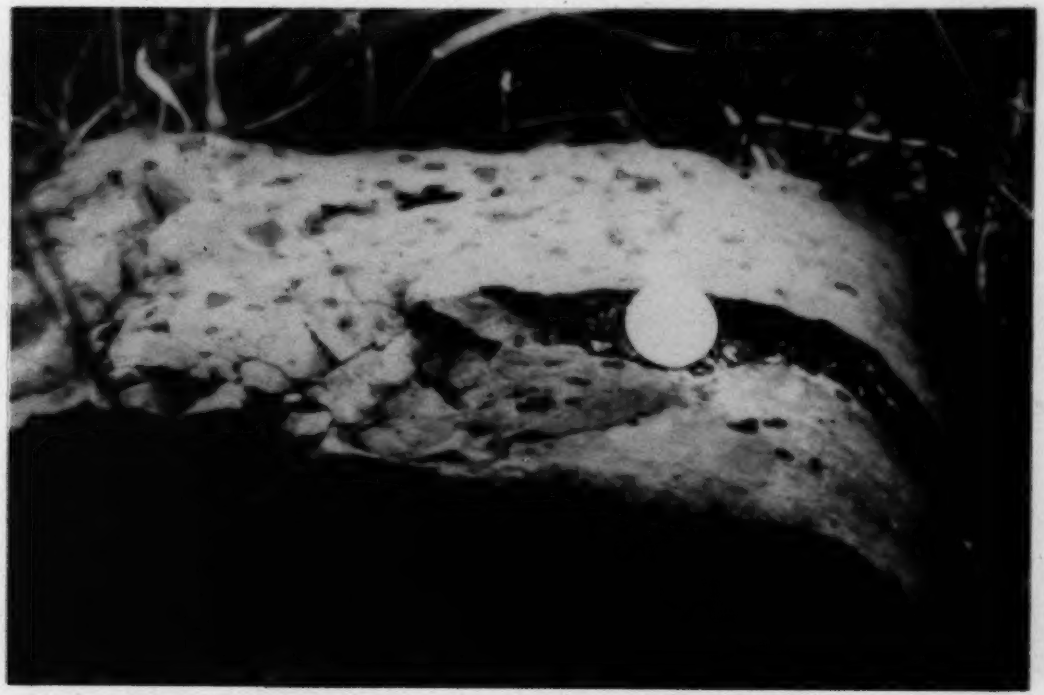


Plate 14 - Weathered Sandstone boulder. Oxidation rind approximately 1cm thick. Duration of weathering approximately 29 years.

Plate 15 - Large oxidized iron concretion contained within a shaly unit. Duration of weathering approximately 29 years.

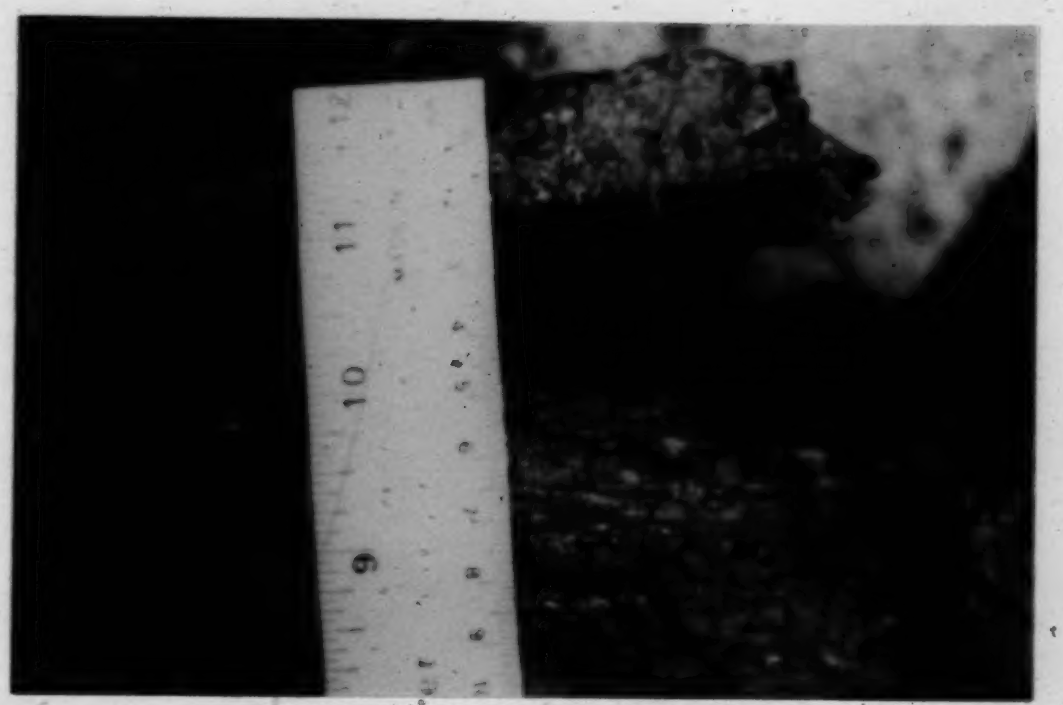


Plate 16 - Coal fragment with shale parting which is highly fractured. Only visible weathering on the coal fragment appears as a duller surface lustre.

Appendix 7

Table 1 - Thin Sections Prepared and Observed

Fig. 1 Weather Rind Thickness on Sandstone

Fig. 2 Weather Rind Thickness on Siltstone

Fig. 3 Weather Rind Thickness on Shale

Table 1

Thin Sections Grassy Mountain

Lithologic Samples (Sand size)

Artificially Weathered	Fresh Samples
1) Coal	2) Coal
3) Sandstone	4) Sandstone
5) Siltstone	6) Siltstone
7) Shale	8) Shale

Particle Size Variations

Artificially Weathered	Fresh Samples
9) Gravel [a]	10) Gravel
11) Sand [a]	12) Sand
13) Silt Clay [a]	14) Silt Clay

Naturally Weathered Overburden Samples

15) Gravel [a] 2cm
16) Sand [a]
17) Silt [a]
18) All Sizes 2cm

a) represents sizes determined by U.S. Standard Sieves and Wentworth classification scale.

Fresh Rock Sample Thin Section Representing Specific Lithologic Units within the Highwall at Grassy Mountain

19)	G8683	Sandstone
20)	G8685	Sandstone
21)	G86813	Sandstone
22)	G86815	Silty Shale
23)	G86817	Sandstone

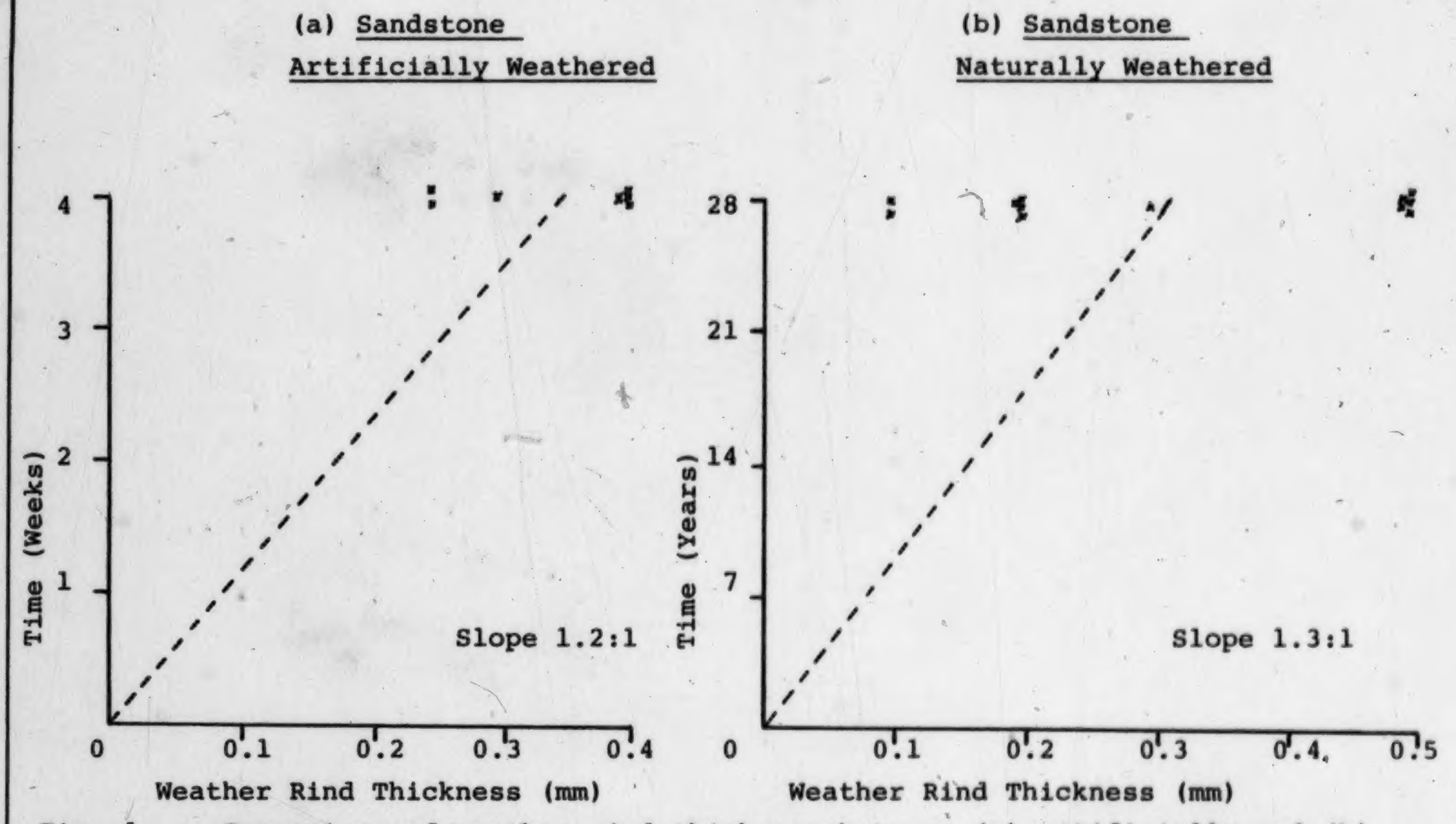


Fig. 1 : Comparison of weather rind thickness between (a) artificially and (b) naturally weathered sandstones. Duration of weathering is known for each variation in the time factor is 354.x. Note similar slopes and average rind thickness which were obtained using a petrographic microscope.

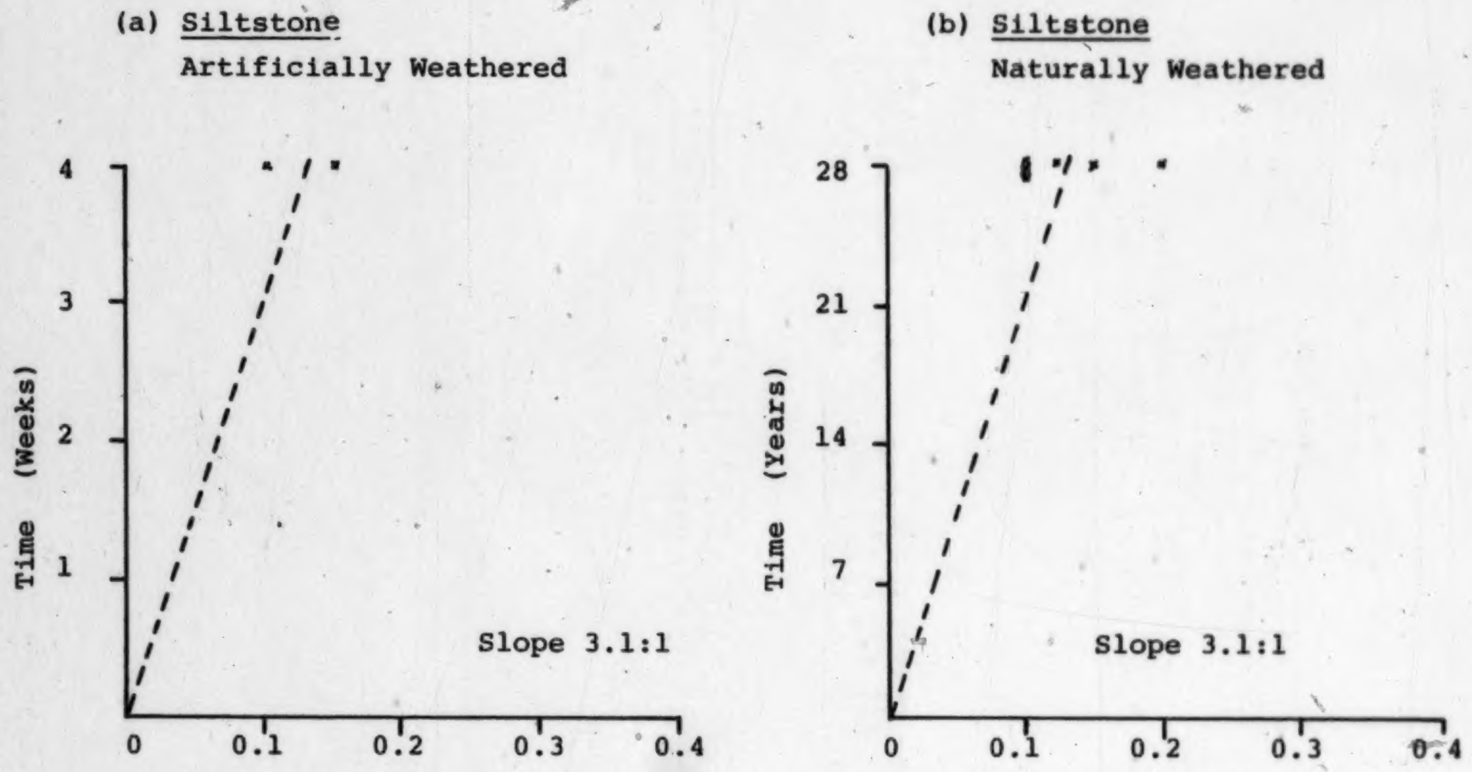


Fig. 2 : Comparison of Weather Rind Thickness between (a)Artificially and (b)Naturally weathered siltstones. Duration of weathering is known for each sample, the time factor difference is 364 X. Rind thickness for siltstones from each set of data are similar as are slope of lines.

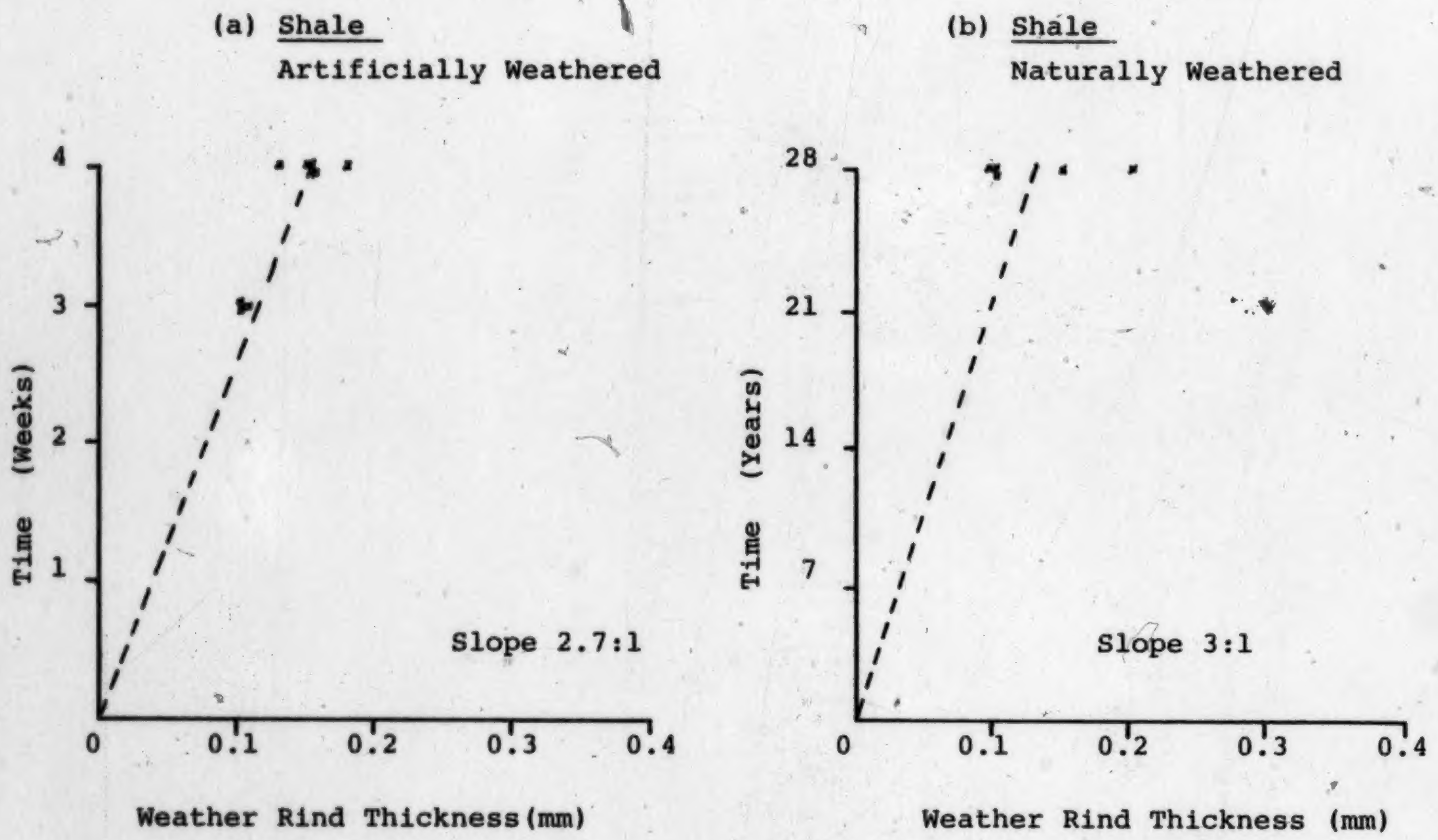


Fig. 3 : Comparison of weather rind thickness between (a) artificially weathered and (b) naturally weathered shales. Duration of weathering was known for each set of samples, the time factor difference is 364 X. Note the similarities in slope of lines and thickness of weather rinds for each set of data.